

LED-Based Solar Simulator

By

Jonathan Honrada

Senior Project

ELECTRICAL ENGINEERING DEPARTMENT

California Polytechnic State University

San Luis Obispo

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Abstract

Solar simulators are great laboratory tools that help users conduct tests with solar cells indoors. Conventional solar simulators typically use xenon arc bulbs as a light source, which can have considerable disadvantages. Recent projects have sought to design and implement LED-based solar simulators, as they are more power-efficient, inexpensive, and durable.

Based on these advantages, the goal of this project is to create an LED-based solar simulator that can replicate the characteristics of solar light, but also be tunable with controls. This broadens the testing capabilities of the device, allowing users to conduct tests with more narrow spectrums of light within the range of 350nm to 1100nm. The device will also be able to replicate different daytime conditions by adjusting the outputted spectral irradiance. The simulator will be able to maintain a uniform spectrum over a single 6" x 6" solar cell with no major deviations in spectral content over time, such that accurate and consistent measurements can be taken during testing sessions.

Chapter 1. Introduction

Solar simulators are laboratory tools that are used to test solar cells and panels. They do so by physically simulating the spectral content and irradiance of sunlight so that photovoltaic testing can be done in a controlled indoor setting rather than outside in direct sunlight. Solar simulators have been used since the 1960s, with the first implementations using carbon arc lamps [1]. Later on, xenon arc lamps became the most preferred light source for solar simulators due to their excellent spectral accuracy and intensity. However, they were high-powered devices that required a lot of maintenance and generally had short life cycles [1]. The pressurized xenon gas used in these lamps also presented a potential hazard for users [2]. Considering these disadvantages, LEDs have been sought out as a more preferable light source for solar simulators. This is representative of a common trend towards LED illumination in many applications [3]. Some of the advantages LED-based solar simulators offer over conventional solar simulators are that they are more compact, less expensive, long-lasting, and consume less power [1][2][3].

There have been several documented successful LED solar simulator designs. One group was able to implement an LED-based ASTM class AAA solar simulator for a $2.3 \times 2.3 \text{ cm}^2$ test area with an extended spectrum into the UV region [4]. Another group was able to implement a self-calibrating LED-based solar simulator that can automatically take solar cell measurements via a computer program while operating [5]. Another group focused their design on keeping costs as low as possible, achieving a respectable near-ASTM class B output over a test area of $3.5 \times 3.5 \text{ cm}^2$. [6]

With respect to the previous considerations and cited works, this project aims to design and fabricate an LED-based solar simulator using LEDs and LED drivers provided by ROHM Semiconductor. This will be done by selecting monochromatic LEDs of various wavelengths, grouping same-wavelength LEDs to be controlled by the same driver, and arranging them on a PCB to achieve stable and even output. The device's performance will be evaluated using the ASTM standards for solar simulators, which provide well-defined metrics for testing solar simulators [4]. The device will also need to be able to output an irradiance of up to 1000 W/m^2 over the desired test area, as this is the typical irradiance of sunlight on a bright, sunny day [7]. Lastly, the device will need to be tunable in a manner where the irradiance of wavelength-based arrays can be adjusted separately from one another and the overall irradiance of the output can be adjusted as well.

A solar simulator of these capabilities would be a great lab tool to have at Cal Poly, and this project could set the groundwork for future senior projects involving solar simulators.

Chapter 2. Customer Needs, Requirements, and Specifications

2.1 Customer Needs Assessment

The customer needs were mainly derived from the project description and Dr. Dolan, the main customer. This project is also sponsored by ROHM Semiconductor who will be providing LEDs and LED drivers. The desired device will need to be able to simulate sunlight, but also have a spectral output that is tunable at individual wavelengths and in overall output intensity. The device will also need to be reliable and durable in a laboratory environment.

2.2 Requirements and Specifications

This device is only intended for testing individual solar cells, which translates to a test area of at least 6"x6" [7]. This also sets a reasonable scope for the project, as a larger test area would require more power and LEDs and, it would also be more difficult to achieve uniformity as the viewing angle of each LED is limited.

Performance-wise, how well a solar simulator can replicate sunlight is defined by the ASTM standards for solar simulators. The standard defines three performance metrics: spectral match, spatial non-uniformity, and temporal stability for a given time. Each metric has different classes as well, ranging from A (the highest) to C (the lowest). The spectral match metric defines how well the spectral output of the simulator matches the actual spectral output of the sun [6]. For this project, the simulator must not only be able to match the solar spectrum but must also be tunable to custom spectrums of light. The next metric is allowable non-uniformity across the 6"x6" test area. ROHM provides intensity-vs-viewing-angle data for their LEDs, which is useful for determining a suitable height that both prevents a spotty output or an output that is not uniform because the outer edges of the LED beam have lost too much intensity [8].

As for device durability, it will be necessary to derate LED currents as specified by their datasheets [9]. To accomplish this, temperature sensors would need to be integrated into the design, measuring ambient enclosure air and PCB temperature near the LEDs. A cooling system may also need to be implemented, as seen in similar projects [4][5][6].

Table 2-1 provides a summary of all marketing requirements and specifications.

Table 2-1. Marketing Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
1,2	Must exceed ASTM Class C requirements [6]. Spectral Match: 0.4-2.0; AM1.5G spectrum Non-Uniformity: 10% Temporal Stability (5 minutes): 10%	ASTM Class C is the lowest class standard of what would be acceptable for an operating solar simulator. 5 minutes was chosen as the temporal stability period, as this is ample time for a user to conduct tests.
1	Must be able to output up to an irradiance of 1000W/m ² over the specified test area	1000W/m ² is the typical solar irradiance on Earth on a clear, bright day [7].
2	Simulator must exceed ASTM Class C Spatial Uniformity requirements for a 6" x 6" test area	6" x 6" is the typical size of a solar cell [7].
1,3	A PC-Based control application that translates a numerical gain to LED irradiance at specified wavelengths. A gain of 100% at a specific wavelength would output the maximum irradiance of the corresponding LED array and a gain of 0% would turn the LED array off. The application will contain at least 1 preset setting for a 'bright, sunny day' output, as previously defined in the second requirement.	An application of this nature allows for easy control and calibration [6].
4	LEDs must not exceed derated current value based on ambient temperature	To prevent lifespan reduction of LED [9].
4	Powered by 120VAC, 60Hz	As both a lab tool and a high-power device, it is necessary to be powered from the wall outlet.
5	Power electronics must be enclosed	To prevent users from touching exposed hot 120VAC wires
4, 6	ROHM LED and LED Constant Current Drivers must be used for illumination circuitry	ROHM is sponsoring this project and providing LEDs and LED Drivers. Use of constant current drivers will ensure a stable LED output for testing purposes.
4	Implement a cooling system	To prevent causing damage to LEDs from overheating
Marketing Requirements <ol style="list-style-type: none"> 1. Can replicate sunlight 2. Evenly illuminates a single solar cell 3. Tunable at individual wavelengths and in overall intensity 4. Durable and reliable in a laboratory setting 5. Safe to operate 6. Must use ROHM LED Drivers and LEDs 		

Chapter 3. Functional Decomposition

3.1 Level 0 Block Diagram

The solar simulator system will require three inputs: input from the user, ambient temperature, and 120VAC power. User input is intensity gain at defined spectral wavelengths and the overall output intensity gain. Ambient temperature and PCB temperature will need to be measured to detect and prevent conditions that would be unsuitable for LED operation. The system's sole output is the light from the LEDs. Figure 3-1 and Table 3-1 summarize the Level 0 system.

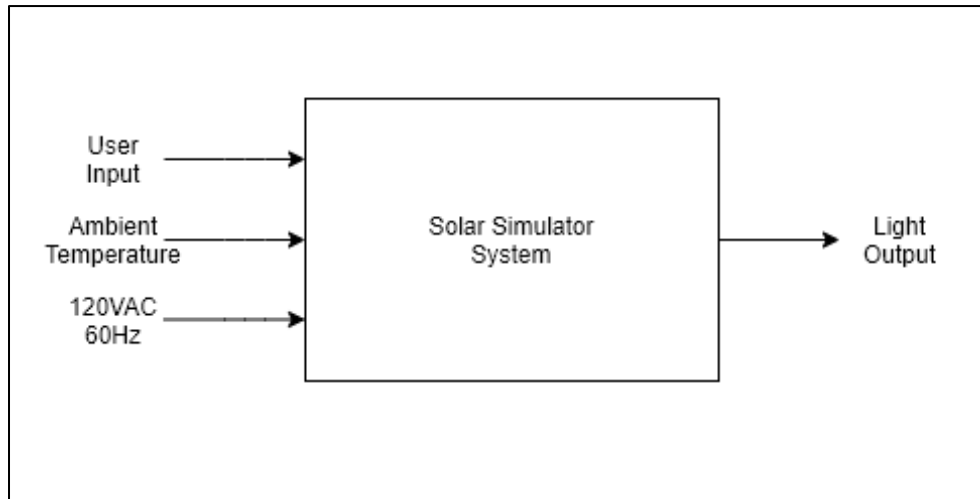


Figure 3-1. Level 0 Block Diagram of System

Table 3-1. Level 0 Block Diagram I/O Description

Module	Solar Simulator
Inputs	<ul style="list-style-type: none">• Ambient Temperature: 0-80°C• User Input: Numerical Values in Computer Application• Power: 120VAC Power
Outputs	<ul style="list-style-type: none">• Light Output: Tunable spectrum of light that can replicate sunlight.
Functionality	Output is a tunable spectrum of light from 400nm to 1100nm. Users can adjust gains at set wavelengths of light as well as overall output gain.

3.2 Level 1 Block Diagram

Figure 3-2 shows the complete Level 1 block diagram of the system. The user will input tuning values into an application on a nearby PC, which will transmit the data to the microcontroller in the solar simulator. The microcontroller will process that data along with data from the temperature sensor to create appropriate dimming signals for the LED drivers. The system power supply converts 120VAC from a wall outlet to appropriate DC voltages for all the sub-components of the solar simulator.

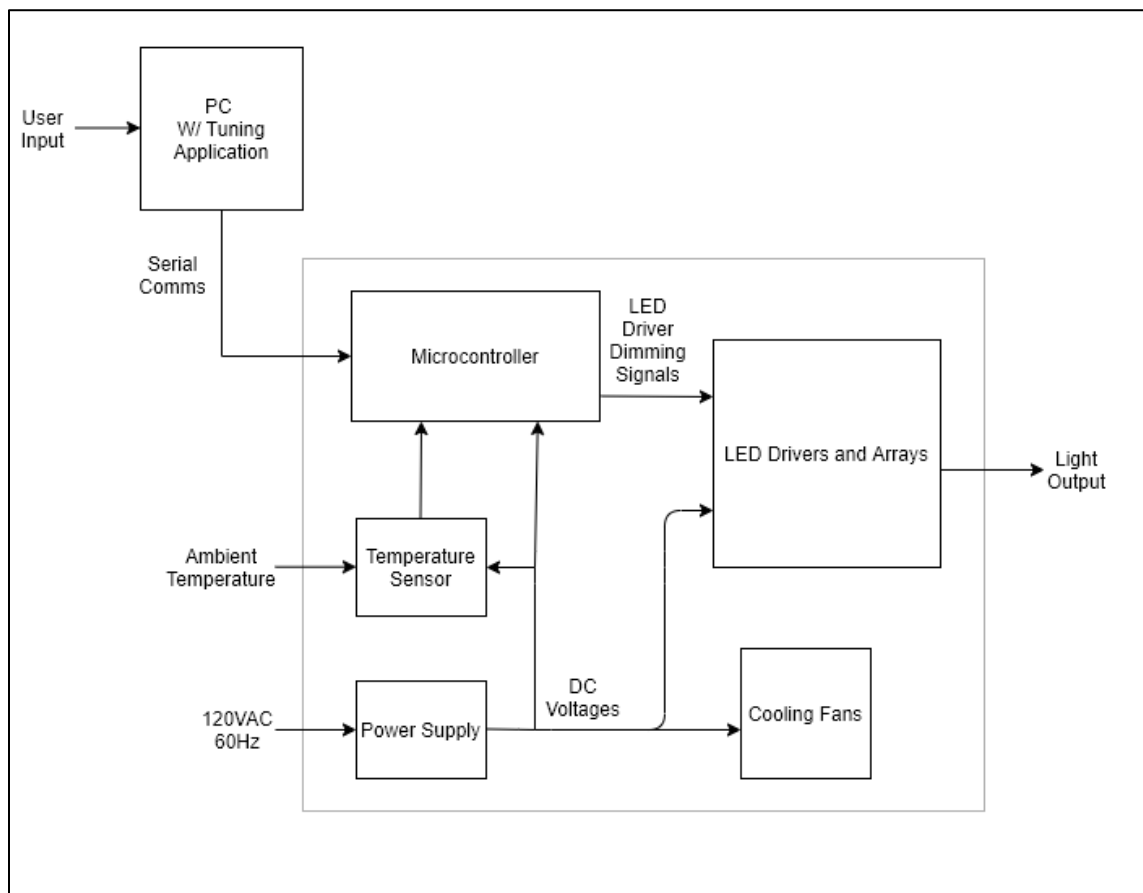


Figure 3-2. Level 1 Block Diagram of System

The temperature sensor is needed to detect overtemperature conditions where it would be necessary to lower LED currents to prevent damage [9]. Tables 3-2 to 3-5 provide input/output descriptions for each subsystem in the level 1 diagram.

Table 3-2. Level 1 Microcontroller I/O Description

Module	Microcontroller
Inputs	<ul style="list-style-type: none"> Power: 9VDC Serial communication with PC Temperature: Serial communications, or analog 0-3.3VDC
Outputs	<ul style="list-style-type: none"> LED Driver PWM Dimming Signals: 0-3.3VDC, 1kHz
Functionality	The controller receives user input for spectral intensity levels at defined wavelengths of light as well as an overall intensity adjustment. It translates these setpoints into control signals for the LED drivers downstream. To prevent LED damage caused by driving at high currents while ambient temperature conditions are high, a temperature input will be used to limit LED current drive.

Table 3-3. Level 1 Temperature Sensor I/O Description

Module	Temperature Sensor
Inputs	<ul style="list-style-type: none"> Ambient Temperature: 0-80°C Power: DC Voltage
Outputs	<ul style="list-style-type: none"> Temperature: Serial communications, or analog 0-3.3VDC
Functionality	The temperature sensor transduces ambient temperature to an analog voltage.

Table 3-4. Level 1 LED Drivers and Arrays I/O Description

Module	LED Drivers and Arrays
Inputs	<ul style="list-style-type: none"> Power: DC Voltage dependent on how many LEDs used LED Driver PWM Dimming Signals: 0-3.3VDC, 1kHz
Outputs	<ul style="list-style-type: none"> Light
Functionality	The LED Drivers and Arrays generate the spectral output of the entire system.

Table 3-5. Level 1 Power Supply I/O Description

Module	Power Supply
Inputs	<ul style="list-style-type: none"> Power: 120VAC Power
Outputs	<ul style="list-style-type: none"> Various Supply Voltages <ul style="list-style-type: none"> Controller: 9VDC Temperature Sensor: 5VDC LED Drivers: DC Voltage dependent on how many LEDs used
Functionality	Receives power from 120VAC outlet and converts it to DC supply voltages.

Chapter 4. Project Planning

4.1 Gantt Chart and Time Estimates

Figures 4-1, 4-2, 4-3 show the Gantt charts for EE460, EE461, and EE462 respectively. All dates have been planned out with respect to Cal Poly's academic calendar. Review sessions and testing sessions at Cal Poly on the Gantt chart can be viewed as windows for a single occurring event rather than a progression towards a due date.

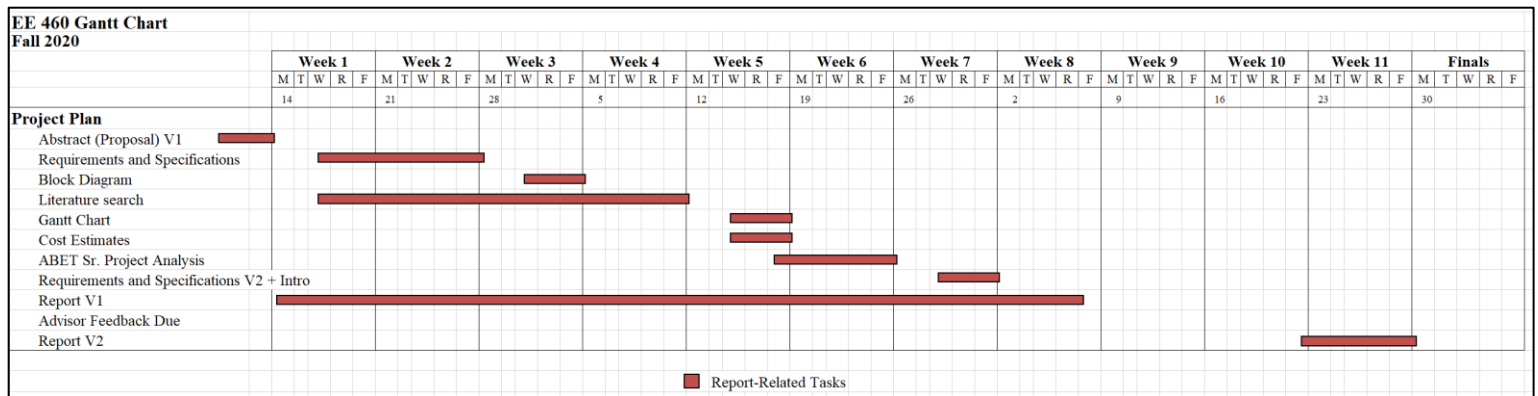


Figure 4-1. EE 460 Gantt Chart

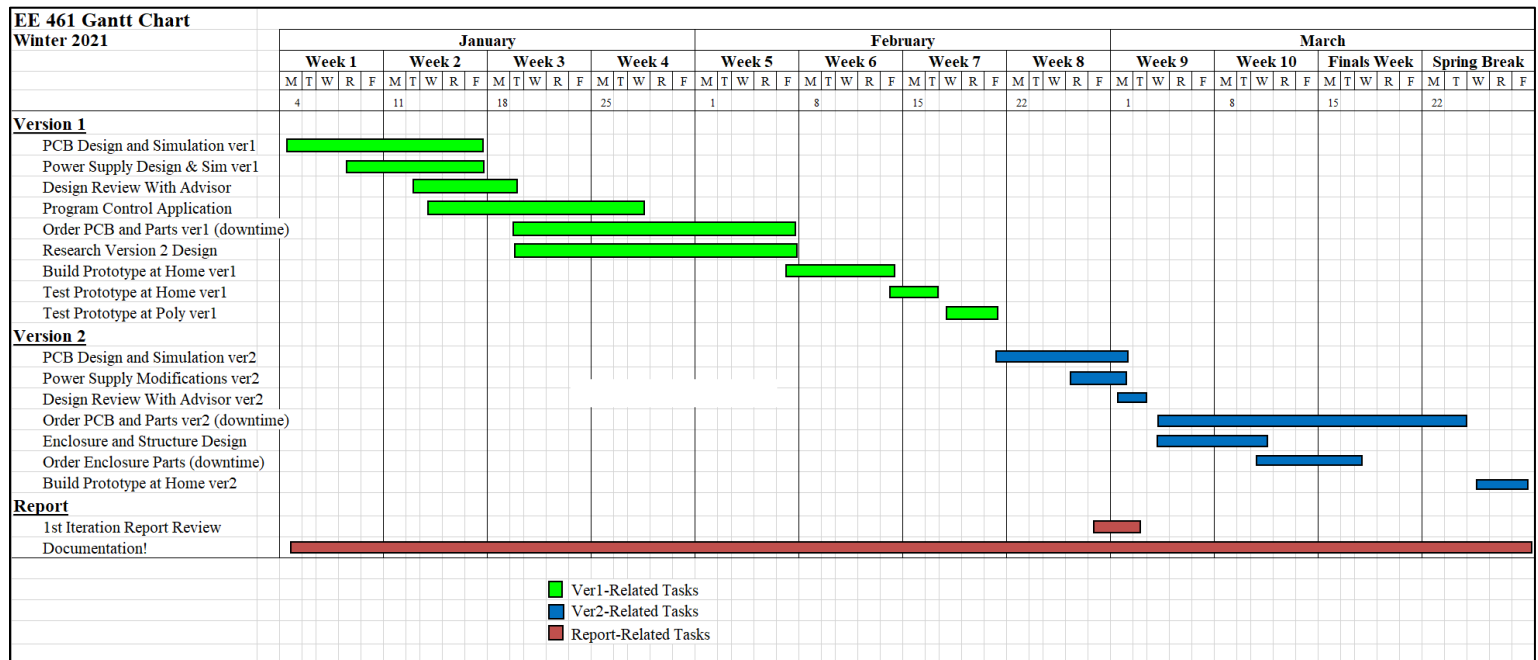


Figure 4-2. EE 461 Gantt Chart

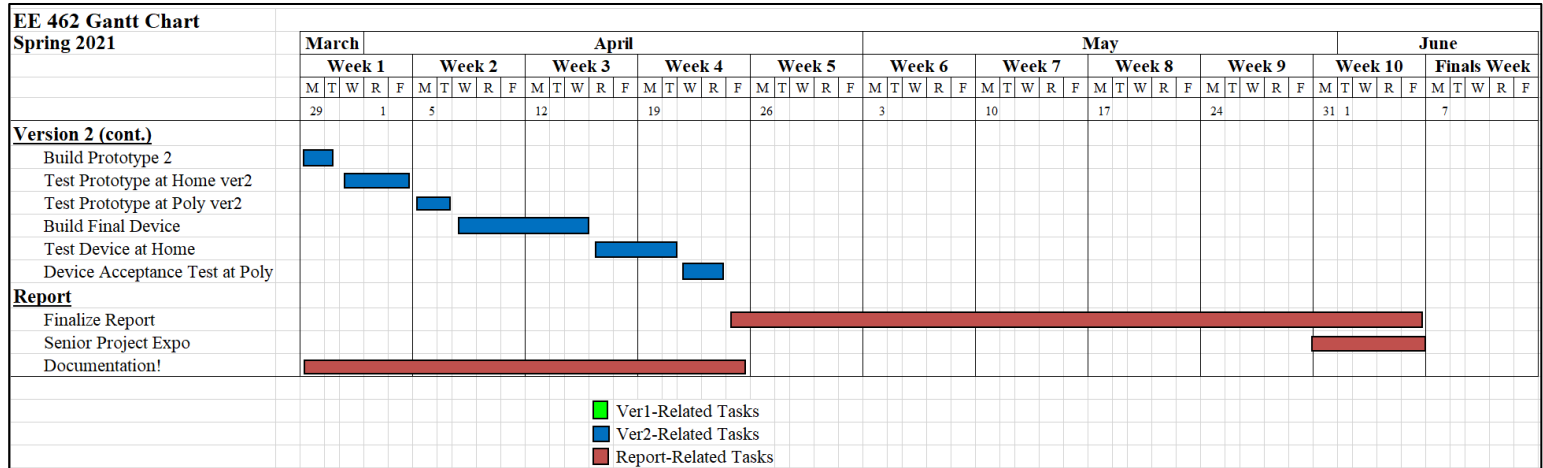


Figure 4-3. EE 462 Gantt Chart

Table 4-1 contains a breakdown of various tasks involved in this project. Equation 10.(1) from *Ford's Design for Electrical and Computer Engineers* was used to derive these estimated times [10]. One workday would translate to about 3 hours of work, to account for time spent on other classes taken outside of EE461 and EE462.

$$t_e = \frac{t_a + 4t_m + t_b}{6}$$

where t_a = most optimistic time
 t_b = most realistic time
 t_c = most pesimistic time

Table 4-1. Time Estimates

Task	Time Estimation (days)	Justification
PCB and Power Supply Design	$t_e = \frac{7 + 4 * 10 + 17}{6} = 10.6$	10 business days is both a reasonable amount of time to spend on PCB and power supply design. For the PCB design, roughly two days will be spent on research, then three to four days on simulations and documentation. The remaining three days will be spent on finalizing the design and PCB layout. Power supply design is delayed a few days on the Gantt chart so that PCB power requirements are defined first. The goal is to choose a power supply that can meet the power need rather than design one from scratch.
Program Control Application	$t_e = \frac{7 + 4 * 10 + 14}{6} = 10.2$	10 days would be a very reasonable amount of time to design and code a PC-based control application for this project. The idea is to set up an initial framework that will be calibrated during prototype testing.

Task	Time Estimation (days)	Justification
PCB Manufacturing and Shipping Down Time	$t_e = \frac{8 + 4 * 15 + 20}{6} * 2 = 29.4$	These numbers were derived from PCBShopper.com, which aggregates prices and shipping times from various manufacturers for a given PCB design. This value is also multiplied by 2 to account for both design phases.
Build Prototype	$t_e = \frac{3 + 4 * 4 + 8}{6} * 2 = 9$	4 working days is realistic since this part is mostly soldering. However, there may be a large number of components involved, as well as time spent on intermittent testing so a pessimistic time of 8 days is also considered. This value is also multiplied by 2 to account for both design phases.
Ver 2 Redesign Phase	$t_e = \frac{4 + 4 * 7 + 12}{6} = 7.3$	The redesign phase should not take as long as the initial design phase, so its realistic completion time is 7 days. However, if a major redesign is needed, a time pessimistic time of 12 days is considered.
Structure and Enclosure Design	$t_e = \frac{4 + 4 * 5 + 10}{6} = 5.7$	5 days would be a realistic time to research structure and enclosure options and develop a suitable design in AutoCAD, as these requirements are mostly spatial in nature.
Build Final Device	$t_e = \frac{4 + 4 * 5 + 8}{6} = 5.3$	5 days is a realistic time to spend on building the final device with intermittent testing considered.
Test at Home	$t_e = \frac{3 + 4 * 4 + 6}{6} = 4.2$	The realistic time of 4 days accounts for both design phases. The pessimistic timeframe of 6 days would account for an extra day of testing if things went wrong.
Test Cal Poly	$t_e = \frac{3 + 4 * 3 + 6}{6} = 3.5$	3 days of testing is the minimum (2 for each prototype, 1 for the final acceptance test). In the event that more testing on campus needs to be done, a pessimistic timeframe of 6 is considered.
Finalize Report	$t_e = \frac{12 + 4 * 14 + 21}{6} = 14.8$	14 days would be a reasonable amount of time to spend on formatting the report, as there is a lot of information to organize and edit. This would also account for time spent with my advisor reviewing my work.

4.2 Cost Estimates

Table 4-2 breaks down and explains cost estimates for this project. The PCB manufacturing and shipping costs utilize Ford's cost estimation equation, while others are defined by selected parts. Most of the electronic components will be sourced from Mouser.com. Structural material may be sourced from McMaster-Carr or could also be 3D printed if access to a printer is available.

Table 4-2. Cost Estimates

Project Component	Cost	Justification
Labor	$\$ \frac{37}{hr} * 224hrs = \8288.00	The 224 hours estimate comes from the total estimated working days in the previous table, not including downtime during shipping. This also assumes that 1 working day is equivalent to 3 hours of work. An hourly wage of \$37/hr is also assumed based on 25% percentile of electrical of engineering wages [11].
Electronics Materials		
PCB Manufacturing and Shipping	$\frac{\$50 + 4 * \$60 + \$100}{6} * 2 = \130.00	These numbers were derived from PCBShopper.com, which aggregates prices and shipping times from various manufacturers for a given PCB design. This value is also multiplied by 2 to account for both design phases. We apply Ford's cost estimation formula (10.(6)) since there are many options to consider [10].
LEDs	$\$27.50 * 2 = \55.00	\$27.50 is the extended cost of 100 ROHM LEDs, multiplied by two to account for both design phases. Price source is Mouser for device SML-Z14V4TT86.
LED Drivers	$\$39.10 * 2 = \78.20	\$21 is the extended cost of 20 ROHM LED drivers, multiplied by 2 to account for both design phases. Price source is Mouser for device BD81A76EFV-ME2.
Power Supply	$\frac{\$25 + 4 * \$27 + \$32}{6} = \27.50	Price source is Mouser for various devices.
Structure and Enclosure Material		
Garolite XX Sheets	$\$10.69 * 3 = \42.00	Electrically insulating rigid sheets, 12"x12", 3/16" thick. These will be used for mounting electronics. Price source: McMaster-Carr product 8525K113
Slippery UHMW Polyethylene 90° Angles	$\frac{\$4.95}{ft} * 2ft * 4 = \39.60	Column supports for planar sheets. Price source: McMaster-Carr product 9852K83
TOTAL COSTS: \$8660.30		

Chapter 5. Design

5.1 Background on Radiometric and Photometric Units

In the process of designing a solar simulator, it is necessary to understand the difference between radiometric and photometric units which are used to characterize the power output of LEDs. The goal of this project is to create a device that can output an irradiance of up to 1000W/m^2 on the test plane, which is a radiometric unit. However, output characteristics for LEDs that emit in the visible light range are typically listed in photometric units (lumens, lumens/ m^2 , etc.) in datasheets. Photometric units indicate the power output of an LED weighted by a spectral luminosity function that approximates a human's sensitivity to visible light [12]. This luminosity function is shown in the figure below.

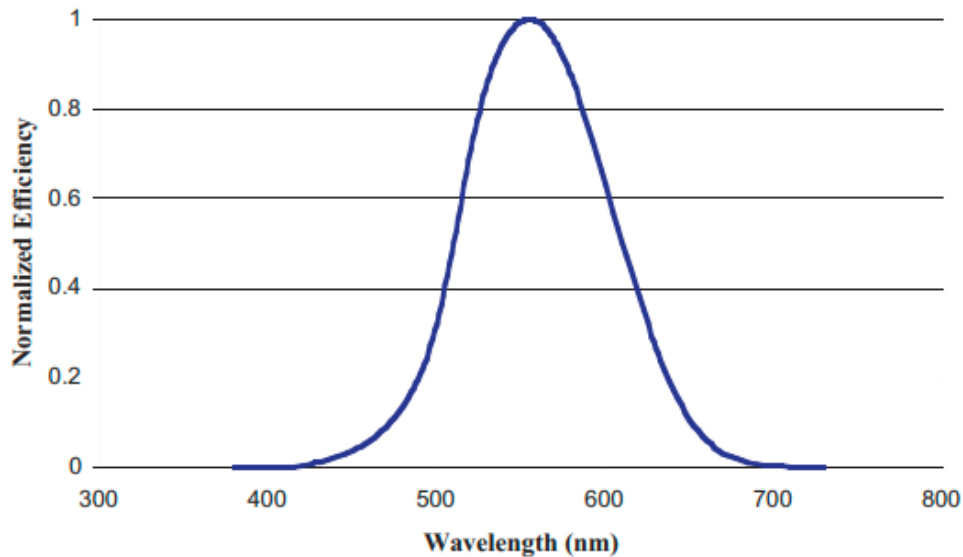


Figure 5-1. The Luminosity Function, $V(\lambda)$ [12]

A radiometric unit can be converted to a photometric unit using the equation shown below.

$$\Phi_V = K_m \int_{\lambda=380}^{\lambda=830} \Phi_E(\lambda) V(\lambda) d\lambda \quad \text{Equation 5-1}$$

Where Φ_V is Luminous Flux in lumens

K_m is a constant of $683 \frac{\text{lumens}}{\text{Watt}}$

$\Phi_E(\lambda)$ is Radiant Flux in Watts

$V(\lambda)$ is the unitless Spectral Luminous Efficiency Curve

Although this is an important relationship to understand, our interest lies in converting photometric data from the provided LEDs' datasheets to radiometric units in order to simulate the output of the proposed solar simulator.

Converting from photometric units to radiometric units can approximately be done using the following equation [13].

$$\Phi_E = K_m \frac{\Phi_V \sum_i f_i}{\sum_i f_i V_i} \quad \text{Equation 5-2}$$

Where Φ_E is Radiant Flux in Watts

K_m is a constant of $683 \frac{\text{lumens}}{\text{Watt}}$

Φ_V is Luminous Flux in lumens

f_i is the spectral distribution function of the LED output (found in datasheet)

V_i is the unitless Spectral Luminous Efficiency Curve

5.2 MATLAB Simulation of LED Array

The simulation method used is described in [14]. From the LEDs that were provided by ROHM, seven wavelengths were chosen to comprise the total spectrum: 470nm, 528nm, 572nm, 590nm, 605nm, 630nm, and 950nm. The majority of LEDs come from ROHM's SML-Z14 family, which have great viewing angles of 114° and high brightness. The exception is the 950nm LED, which is not of the SML-Z14 family. It has a good power output but a poorer viewing angle of 36° . Overall, high brightness and larger viewing angles are preferred so that the light can be spread more evenly across the test plane.

The setup for the device involves an LED array above a test plane at some set height. In order to ensure even lighting of a 6" x 6" test plane, the area of the LED array must be larger than the specified 6" x 6" test plane. This setup is shown below in Figure 5-2.

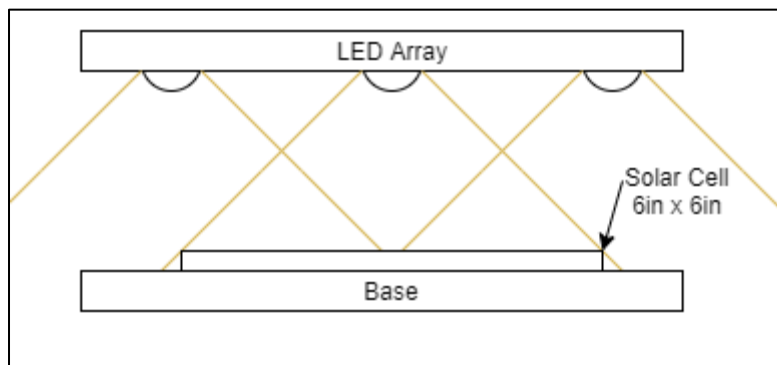


Figure 5-2 Device Setup to be Simulated

In the MATLAB simulation, individual LEDs were divided into groups by wavelength and assigned positions on the LED array using x-y coordinates. In MATLAB, this corresponds to creating an n-x-2 matrix with x-y coordinates for individual LEDs, where one row represents a single LED, the first column represents the x-coordinate on the LED array, and the second column represents the y-coordinate. Each wavelength has its own associated LED position matrix. The MATLAB simulation code can be found in Appendix B.

There were not many resources on optimal LED placement. It was eventually decided to have an alternating pattern of LED columns with each column dedicated to one wavelength of radiation.

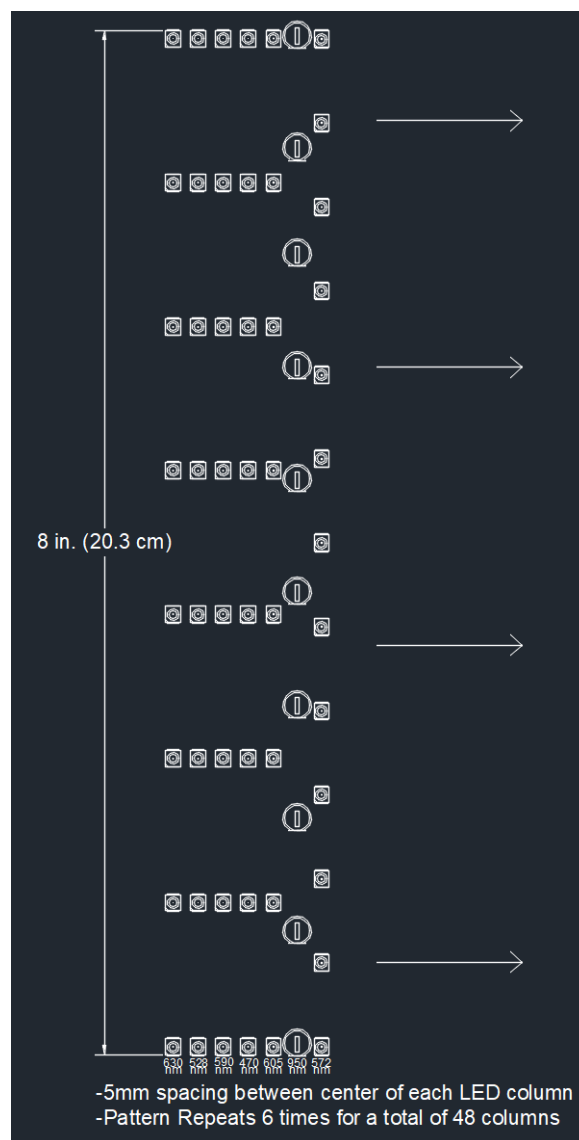


Figure 5-3. “Repeating Columns” LED Placement Pattern

Table 5-1. Summary of LEDs Used

Wavelength(nm)	Part #	# Per Channel	Total
950	SIR-56ST3F	10	60
630	SML-Z14V4T	8	48
605	SML-Z14D4T	8	48
590	SML-Z14Y4T	8	48
572	SML-Z14M4T	13	78
528	SML-Z14EGT(A)	8	48
470	SML-Z14BGT(A)	8	48
			378

With all LEDs placed, a photometric intensity map in lumens/m² for each wavelength is computed using the equation below [14].

$$E_v = \frac{I_v}{2\pi * d^2} \cos^m \left(\frac{\theta}{2} \right) \quad \text{Equation 5-3}$$

Where

E_v is Illuminance in lux

I_v is luminous intensity in $\frac{\text{lumens}}{\text{sr}}$

d is distance from LED to a point on the test plane

m is a cosine scaling factor dependent on LED viewing angle

θ is the angle between LED beam center and point on the test plane

These photometric intensity maps in Lumens/ m² are then converted to radiometric irradiance maps in W/m² using the formula described in equation 5-2. Essentially, all the values in the map are multiplied by the resulting conversion factor.

With an LED array size of 8.5” x 8.5” suspended 4.5 cm from the test plane, a max irradiance of 75.85 W/m² was recorded around the center of the test plane. The resulting non-uniformity was calculated to be 9.17%, which would make it Class C in this regard. The resulting irradiance map is shown below in Figure 5-4.

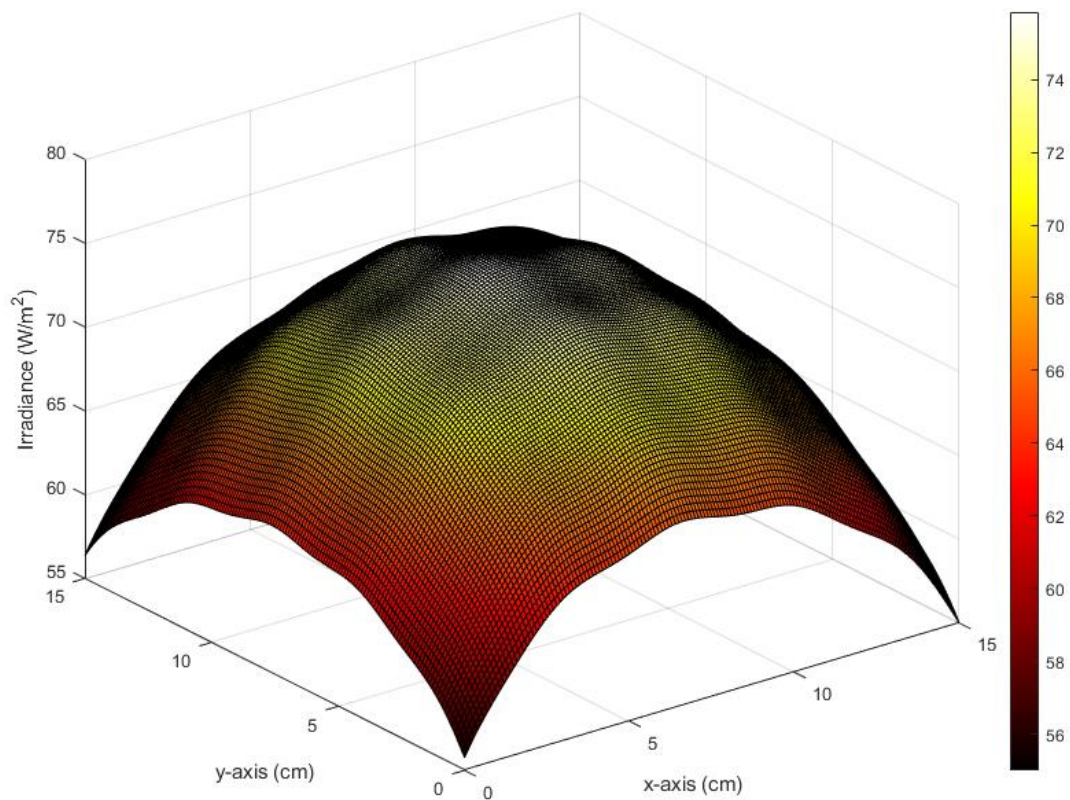


Figure 5-4. Simulated Solar Simulator Irradiance

As for spectral content, we were able to achieve good spectral coverage from 430nm to 670nm and some coverage in the IR region due to the inclusion of the 950nm LED. Figure 5-5 below shows the combined spectral output of the simulated solar simulator. By tuning via scaling each wavelength with a coefficient between 0 and 1, Class A spectral match can be achieved in the visible light region. This requires the irradiance output of the 950nm LEDs to be a lot higher compared to the rest of the LEDs.

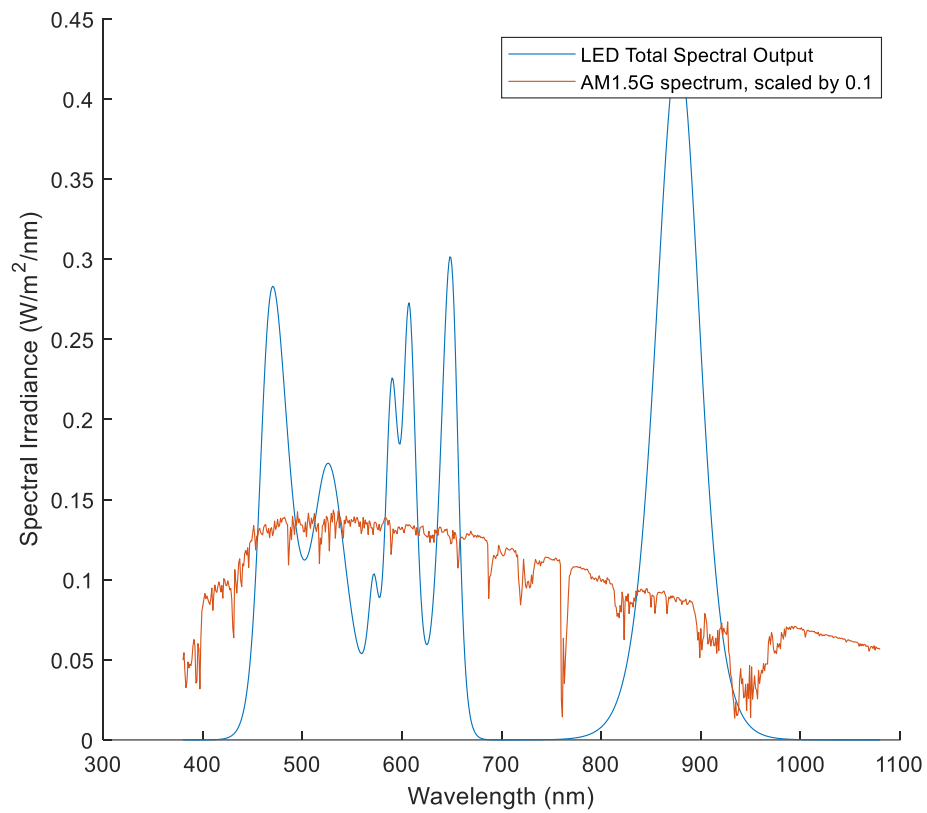


Figure 5-5. Simulated Spectral Output of Solar Simulator

With the LED positions simulated and finalized, the following PCB array was built in KiCAD. It was designed to operate with any 6+ channel LED driver, where each wavelength is controlled by one driver.

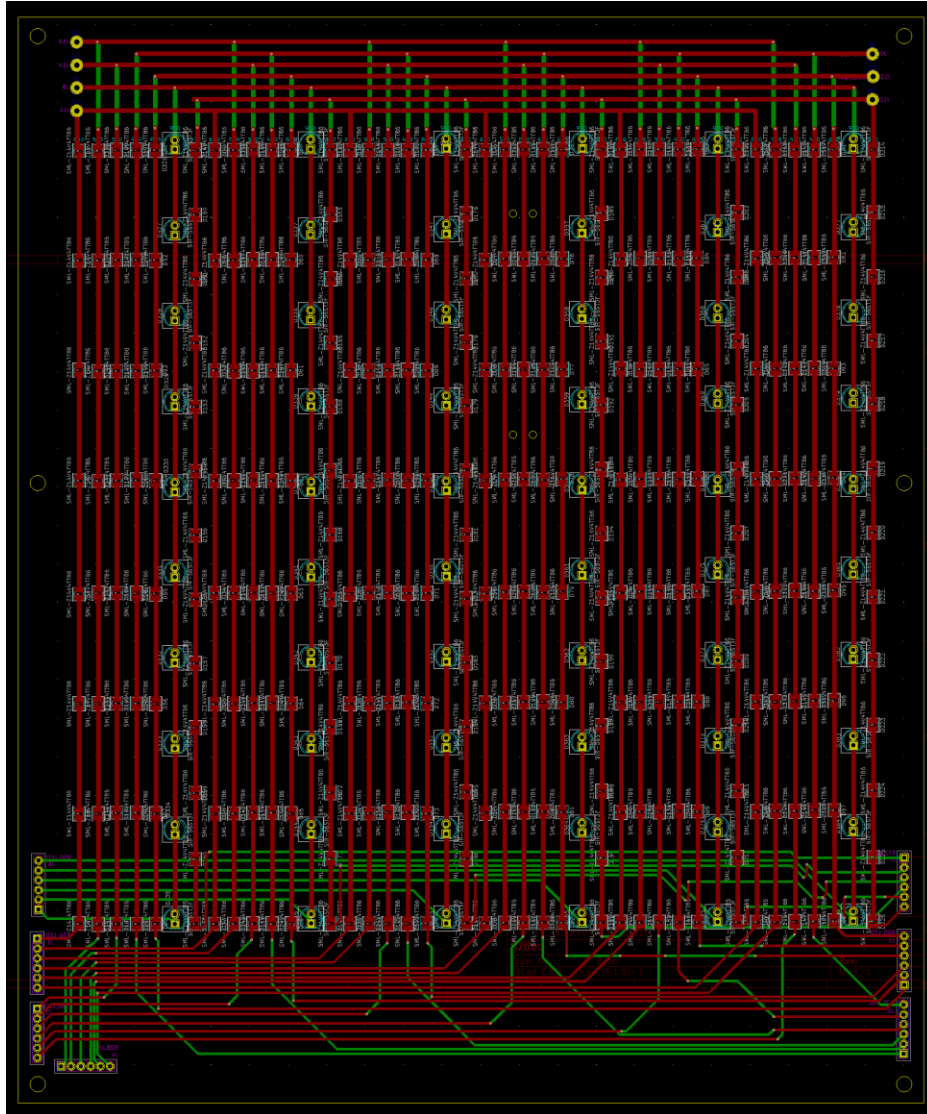


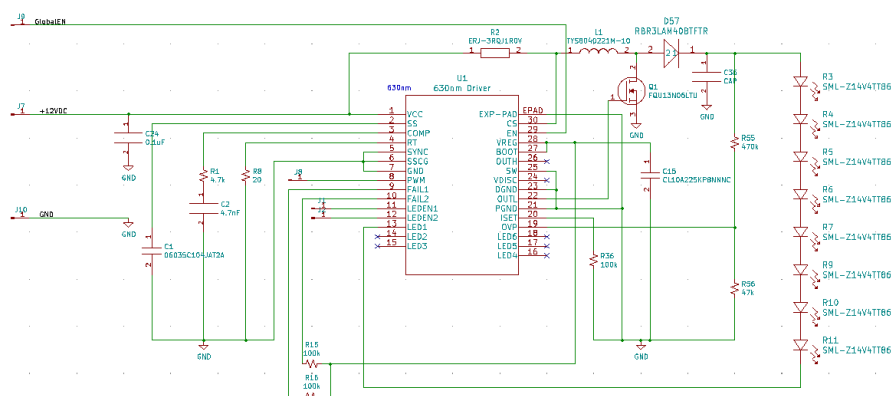
Figure 5-6. LED Array PCB Design

5.3 LED Driver Testing

For the final device, each wavelength will have one driver controlling the intensity of all associated LEDs. From the provided parts, ROHM's BD81A76EFV-M buck/boost driver and BD8388FV-M open-drain driver were chosen as potential candidates. The buck/boost driver was preferable to the other, as it had a higher-rated maximum current which allowed all LEDs to run at their rated current with no issues. It also offered constant-current control which corresponded with one of the requirements of this project. The downsides of the buck/boost driver are that it requires a lot of extra components to function properly, which makes it more complex and difficult to operate. On the other hand, the open-drain driver is

much easier to operate, and only requires current-limiting resistors for each channel and a microcontroller to drive its digital output control. However, the open-drain driver has a max rated current of 50mA per channel, which is the same rated current for some of the LEDs in this project. This means some LEDs will have to function at slightly lower than their rated current in order to protect the driver.

Test PCBs were built for both drivers. The schematics for these test circuits are shown below.



ohms.” However, even after replacing the incorrect resistor with the correct one, the driver still did not operate as intended. Testing for shorts and opens also did not yield any potential cause for the driver not operating.

After further review, it was determined that these drivers were not suitable for this application, as there was no way to vary the LED current. Instead, Analog Device’s LT3760 Boost LED driver was chosen, as it can drive a variable current through 8 LED channels. The maximum current per channel is set by a single resistor. LED current can then be varied (referred to as analog dimming) by varying the voltage at the CTRL pin from 0 to 1 volt. The LED current is then linearly prorated, where an input voltage of 1V results in max current per channel and an input voltage of 0V results in no current flow. Each LED channel feeds into one of the eight current-sink inputs and, they all share one common boosted voltage. This can be seen in the application circuit below.

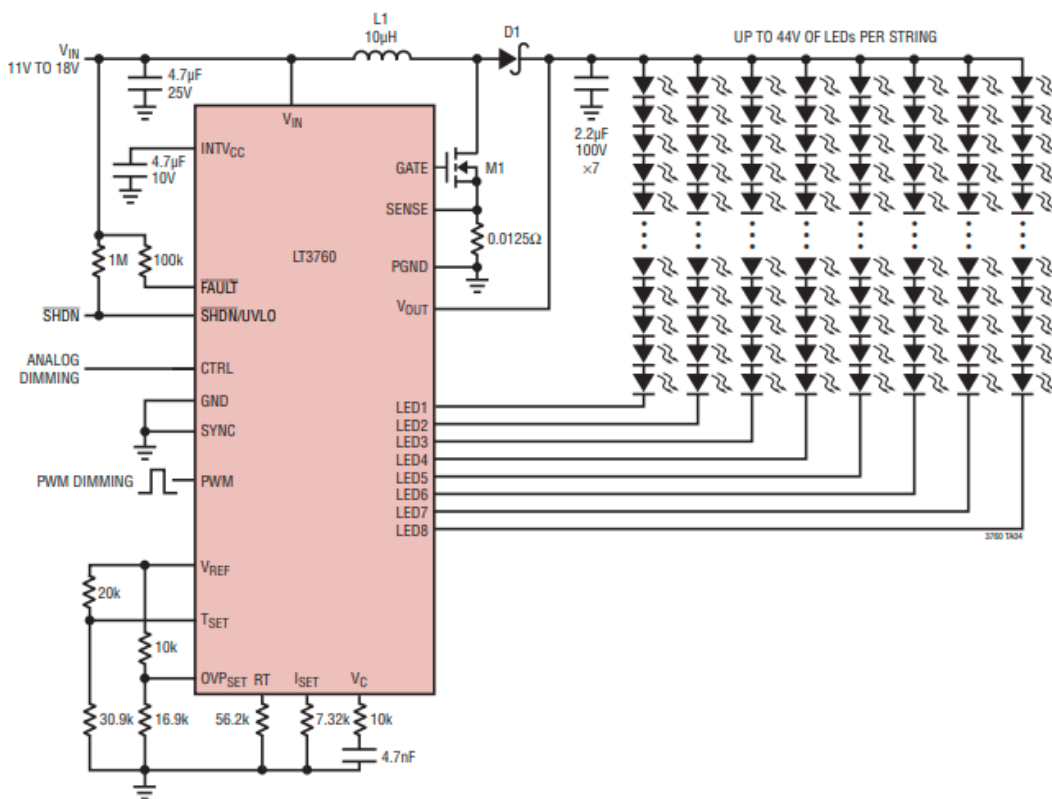


Figure 5-9. LT3760 Example Application Circuit

The LT3760 driver was then simulated in LTSpice with component values chosen based on the formulas and methods described in the datasheet. Figure 5-10 shows the simulated driver circuit for the 528nm LEDs and 470nm LEDs (both these LED groups will use

separate identical driver boards). Similarly, the 630nm, 605nm, and 590nm will use identical driver circuitry as their loads are very similar. Other than that, the 950nm and 572nm will have their own distinct driver circuitry respectively.

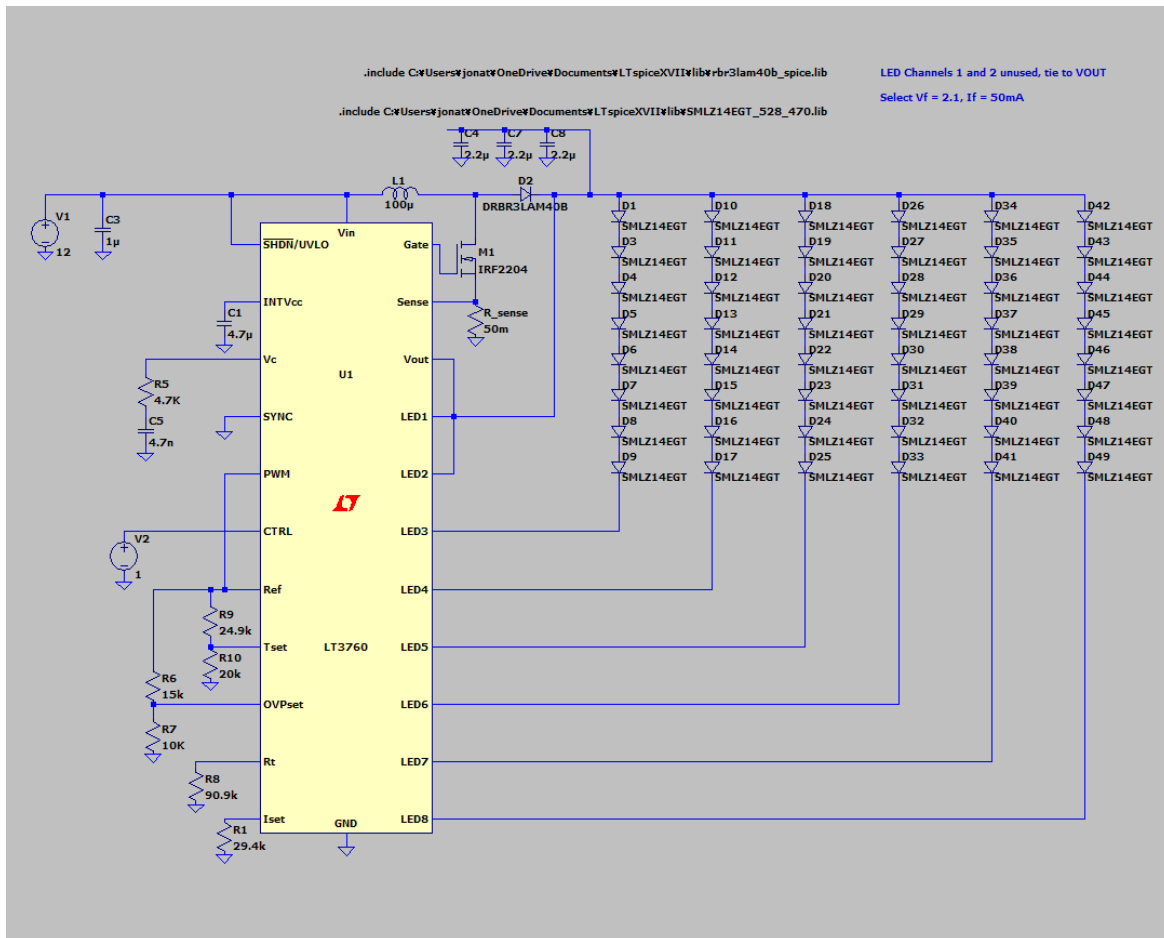


Figure 5-10. Simulated LT3760 Driver Circuit for 528nm and 470nm LEDs

Simulations showed the driver operating as intended, with LED current linearly following the input voltage. Figure 5-11 shows simulation results from LTSpice. The driver is able to properly adjust the LED channel current from 0 to 50mA in response to a control voltage input from 0 to 1V.

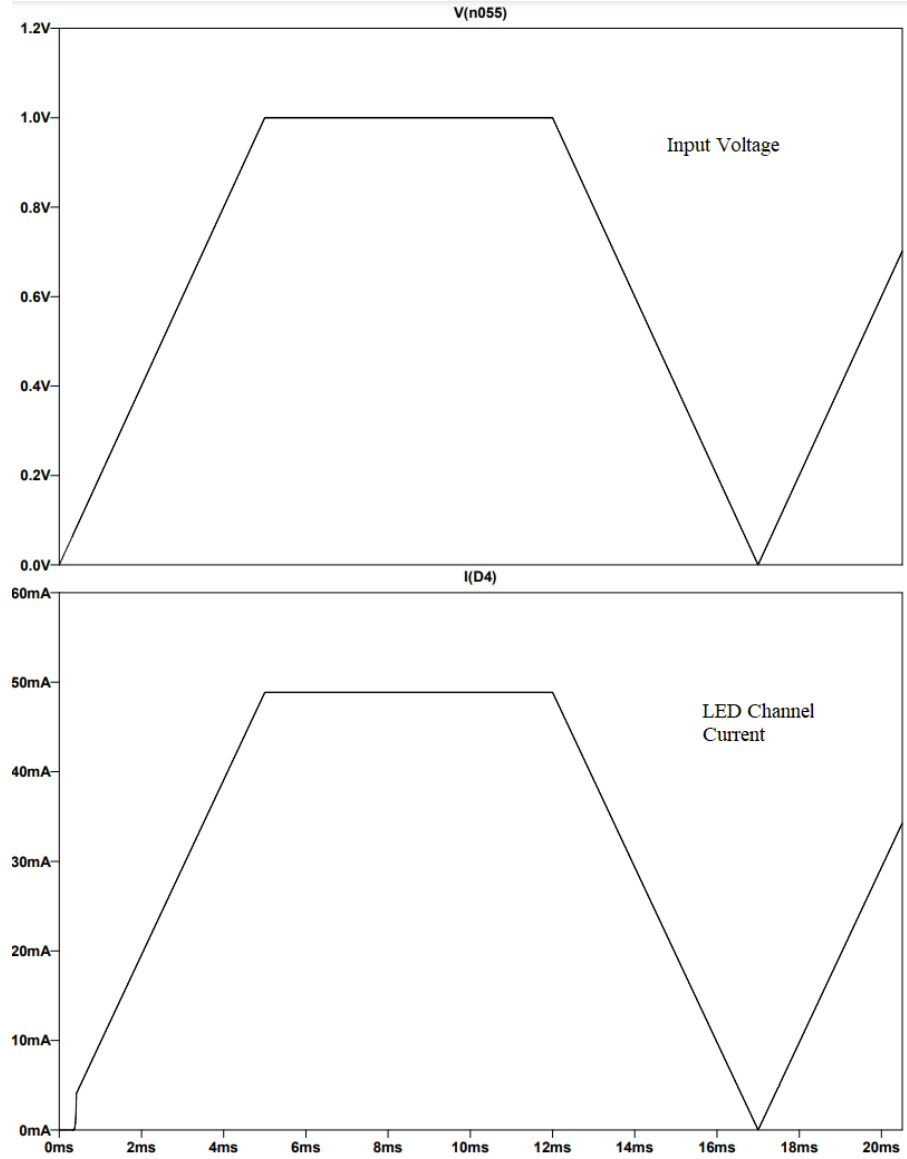


Figure 5-11. Simulated Input Control Voltage and LED Output Current

In order to facilitate easy control from an Arduino, a circuit was designed to convert the Arduino's 590HZ 0-5V PWM signal into a 0-1V signal. This circuit simply consists of a low-pass filter followed by a voltage divider and an additional output capacitor to reduce output noise. This circuit is shown in Figure 5-12.

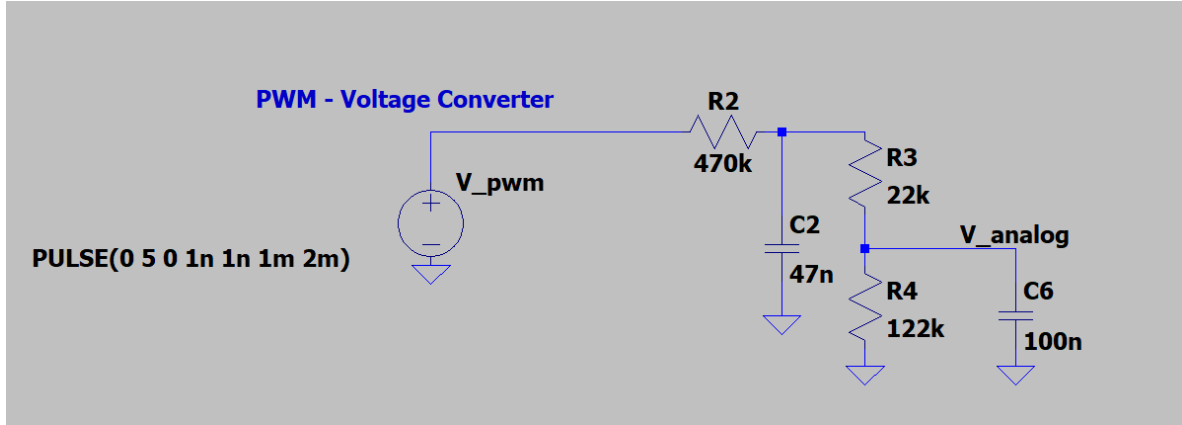


Figure 5-12. Circuit for Converting 5V 490Hz PWM Signal to 0-to1V Analog Voltage

For the purpose of physical testing and prototyping, a PCB using the LT3760 was designed to drive a reduced load of one channel with 8 LEDs. In this setup, the driver will boost 12VDC to 16.8VDC at a maximum LED current of 50mA. Unused LED channels are connected to the VOUT pin. After confirming correct operation with another simulation of the reduced load LTSpice, the PCB shown in Figure 5-13 was designed.

The main goals of this prototype include: (a) verifying the operation of current control via PWM, (b) verifying the integrity of PCB design, and (c) looking at heat dissipation. Lessons were learned from working with the previous ROHM buck/boost driver. Rather than individual traces, copper pours were used for the +12V and GND planes. Traces were properly sized for anticipated current. Additionally, the MOSFET-Diode- \rightarrow C_{OUT} loop was designed to be as short as possible, as the inherent inductance of this loop can create voltage noise on the output ($V = L \cdot di/dt$) [15]. Also, X7R capacitors were for the C_{IN} and C_{OUT} capacitors, as recommended by the datasheet for their improved stability versus temperature changes.

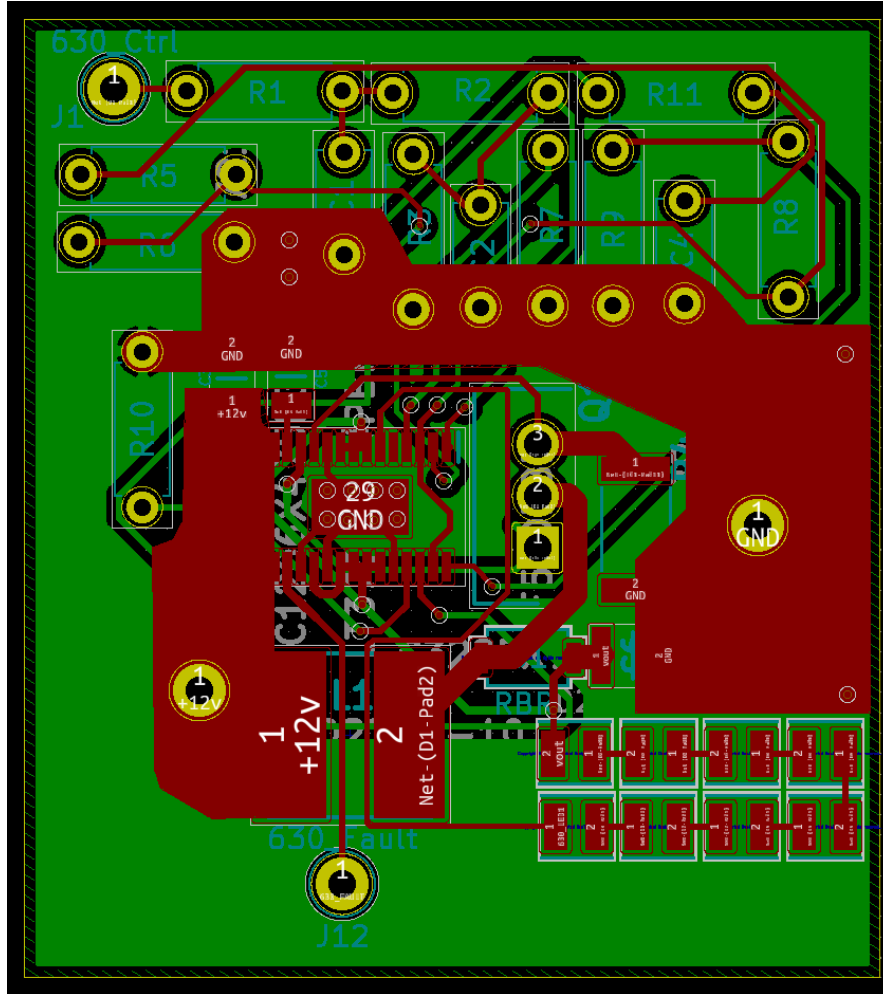


Figure 5-13. Prototype PCB

Physical testing of the prototype PCB was successful. LED channel current was measured with a multimeter with the PWM signal applied to the control pin. Current values were recorded for different values of input duty cycles. These measurements plotted vs duty cycle are recorded in Figure 5-15. Current follows a fairly linear relationship with the duty cycle input but appears to saturate slightly near maximum duty cycle. The maximum current reached at 100% duty cycle was 48.3mA. Additionally, the fact that everything worked as intended also indicated that the PCB design for this load was also good.

Since the original prototype design did not have a separation in the LED channel to measure current, a small modification had to be made. The bottom right LED in Figure 5-13 was removed then soldered onto a separate piece of protoboard. Then wires were soldered onto the pads so current measurements could be made with the multimeter in

between. A small, but important lesson was learned: think about what you want to measure and how you are going to measure it beforehand.

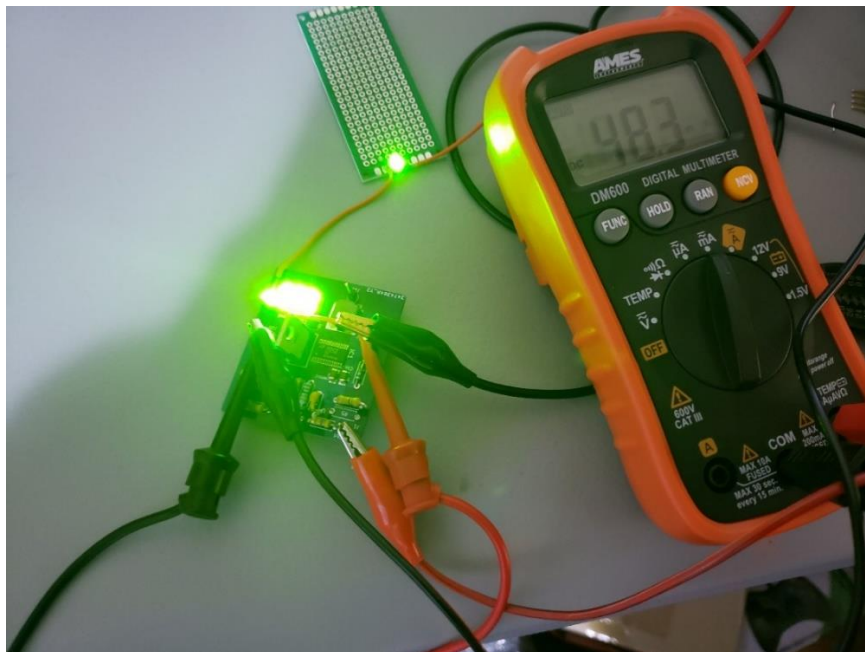


Figure 5-14. Physical Test Setup with Prototype PCB

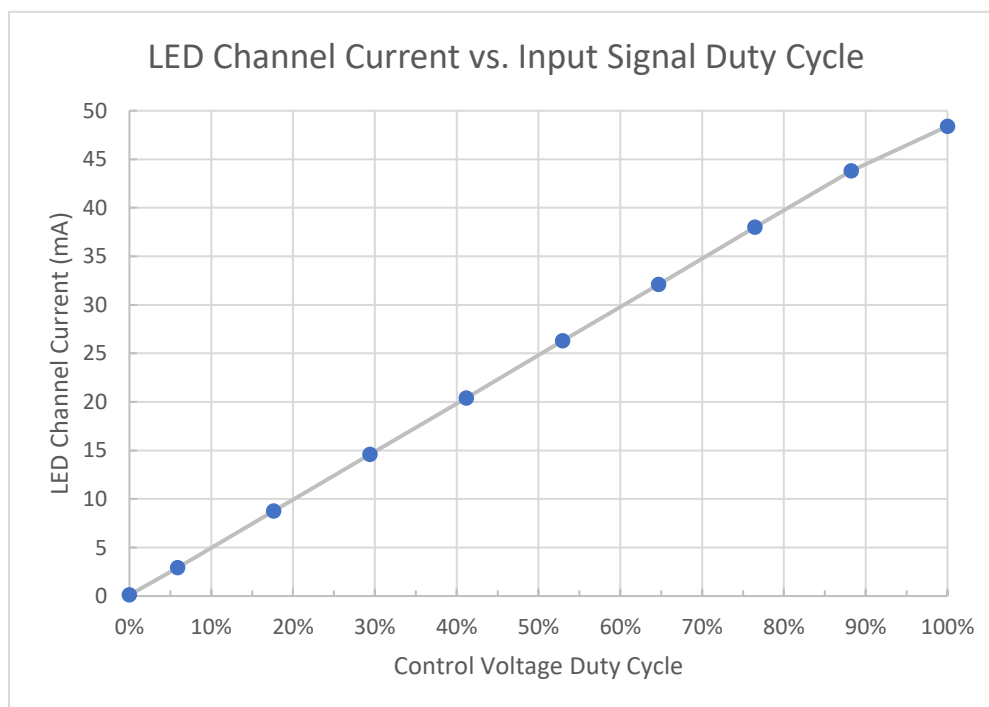


Figure 5-15. Experimental LED Channel Current vs. Input Duty Cycle

Physical testing also provided an opportunity to look at the heat dissipation characteristics of the LEDs. The total power dissipation from the channel was 0.75 Watts. At a max current of 48.3mA, the LEDs reach a temperature of 44.5°C after 5 minutes. After 30 minutes at 48.3mA, the temperature appeared to stabilize at a maximum of 50.3°C towards the top of the array. For reference, the room temperature was at around 21°C.

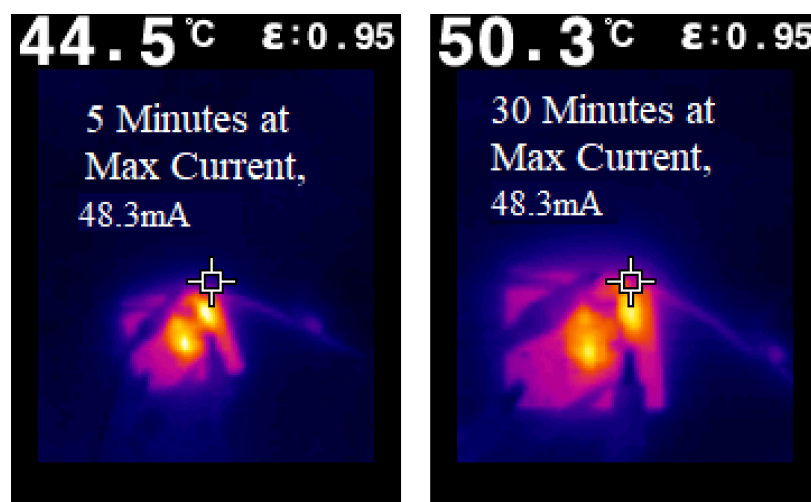


Figure 5-16. Thermal Imaging of Prototype PCB at Max Current

According to the current derating graph for the SML-Z14T series LEDs, this is not hot enough to warrant current derating. Still, to prevent any potential thermal issues with the final device, the LED array board will be made as a metal core PCB with an aluminum core in the middle. This type of construction is common in high-power LED applications. This construction also does not allow the use of a heatsink, but it will still provide much better heat dissipation than a typical FR4 board.

With the prototype functioning well, the final driver PCBs were designed. One of these driver boards is shown in Figure 5-17. There are two models of PCBs that will be used due to a difference in inductor footprints for the 470nm and 528nm wavelengths versus all the other wavelengths. The 470nm and 528nm wavelength LEDs will be driven using what I refer to as the “Type B” board, whereas all the other wavelengths will be controlled with a “Type A” board.

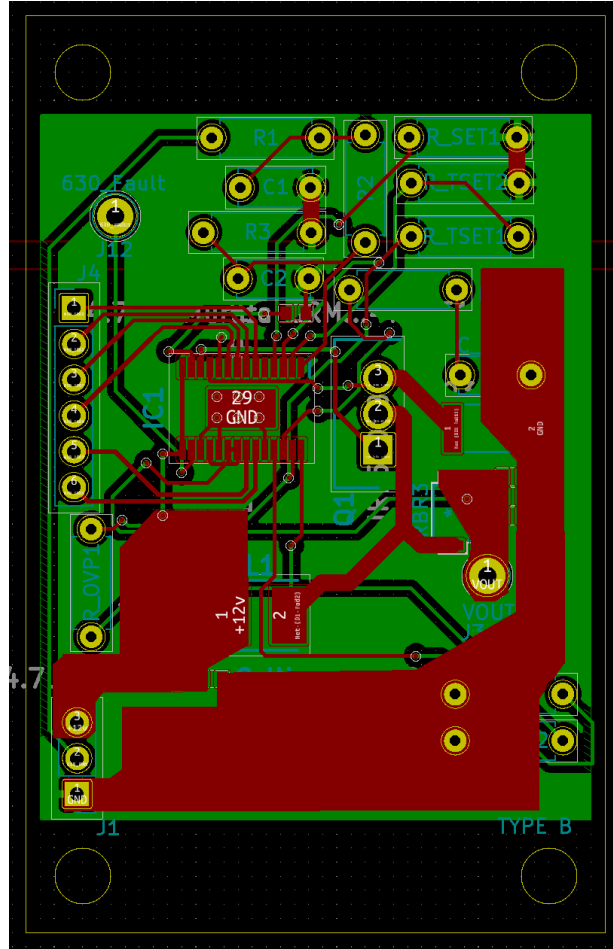
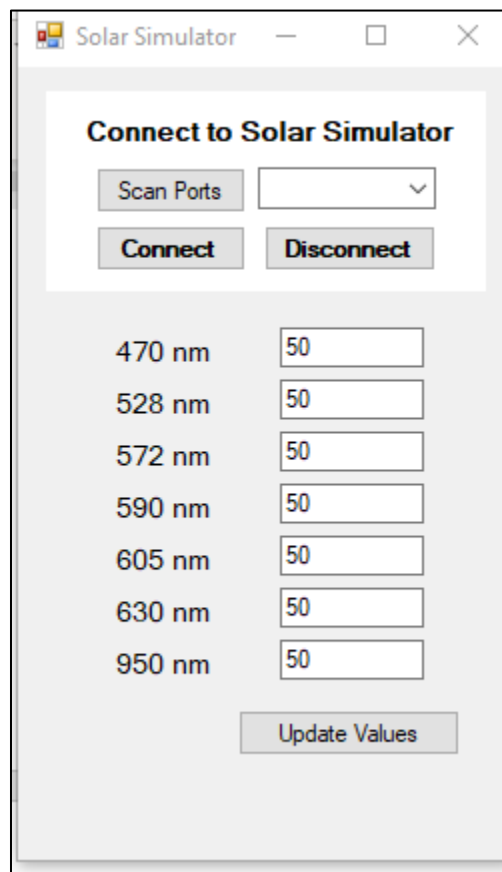


Figure 5-17. Finalized Driver PCBs

Unfortunately, there was difficulty in getting the boost functionality to work on the driver boards. Although a specific cause was never identified, it could have been due to changes in the board layout from the previous prototype. Despite this, the boards were still usable, as the drivers can bypass the boost functionality and operate as intended in a $V_{in} > V_{out}$ condition. This resulted in having to use two separate power supplies to power the LED drivers. An 18V power supply was used to power the 950nm, 630nm, 605nm, and 590nm drivers, and a 36V power supply tuned to output $\sim 31V$ was used to power the 572nm, 528nm, and 470nm. Two separate power supplies had to be used to minimize the excess voltage drop across the LED driver ICs. Too high of a voltage drop would result in excess power dissipation and device failure.

5.4 Computer-Based Control Application

To facilitate easy tunability of the solar simulator, the following computer-based application was created. For an individual wavelength, the user can enter a percentage value from 0 to 100 which corresponds to intensity control for that specific wavelength. This application connects to an Arduino via UART, and sends all this numeric data once the user hits “Update Values.” These values adjust the duty cycle outputs of the Arduino which will be used to control the output intensity of the driver boards.



The screenshot shows a window titled "Solar Simulator" with a standard Windows title bar (minimize, maximize, close buttons). Inside the window, there is a section titled "Connect to Solar Simulator" containing a "Scan Ports" button, a dropdown menu, and "Connect" and "Disconnect" buttons. Below this, there is a list of seven wavelengths with corresponding input fields: 470 nm, 528 nm, 572 nm, 590 nm, 605 nm, 630 nm, and 950 nm. Each input field contains the number "50". At the bottom of the list is an "Update Values" button.

Wavelength (nm)	Intensity (%)
470 nm	50
528 nm	50
572 nm	50
590 nm	50
605 nm	50
630 nm	50
950 nm	50

Figure 5-18. Control Application

To prevent bad values from being written to the Arduino, the application checks if the values entered are numeric, in the correct range, and in the correct format. If not, it will throw an error message at the user informing them of what is causing the error. To prevent data transmission errors, check bytes have been added at the beginning and end of each transmission. If these values do not match the specified value, PWM control values in the Arduino will not be overwritten.

5.5 The Complete Device

Figure 5-19 shows the final anticipated device with all components integrated together. It has two levels constructed from 16"x16" HDPE boards. The bottom level has an 8.6"x8.6" cutout in the middle upon which the LED array board will be mounted. Below this cutout is the intended test area where the solar cell under test will be placed. The driver boards and Arduino will be mounted around the LED array on the same level. Due to there being no room on the first level, the +12VDC power supply will be mounted on the top level. The distance from the bottom of the legs to the first level is 2.2 inches.

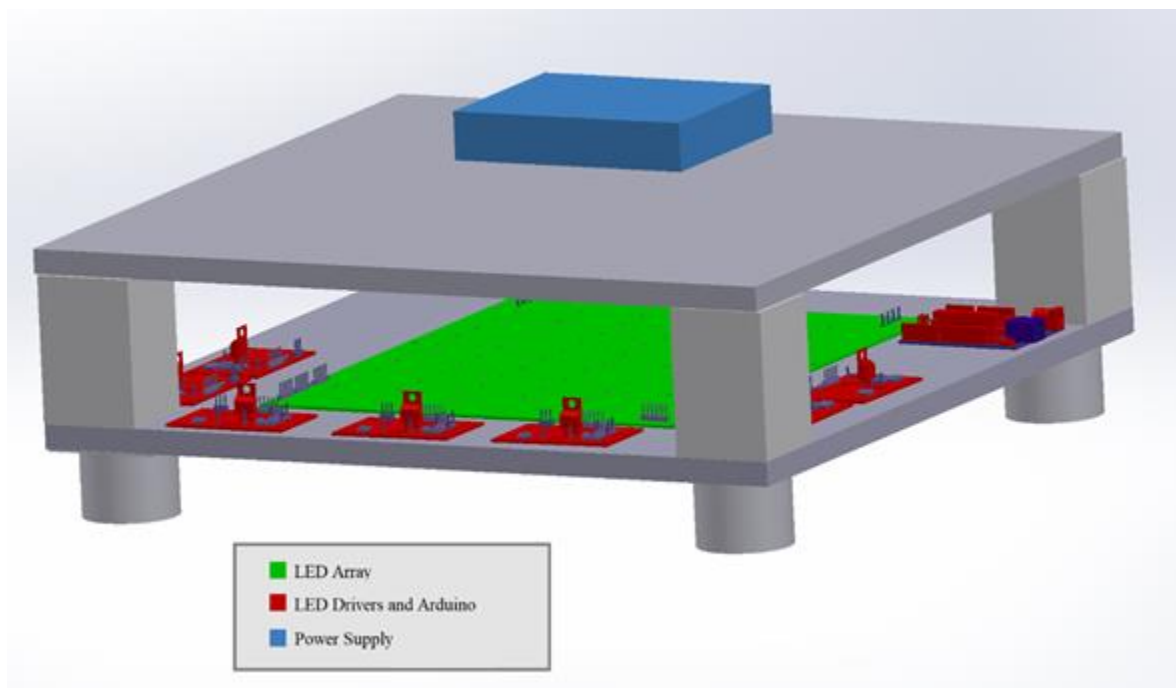


Figure 5-19. Complete Solar Simulator Device

Chapter 6. Physical Testing

6.1 Physical Device

Shown below in Figure 6-1 is the complete physical device, build as described in Section 5.5. There is an 8.6" x 8.6" square cutout at the center of the bottom plane, where the light from LEDs shines down from. The two power supplies are housed in the plastic enclosure on top of the device, with a rocker power switch on the outside for powering on the device. The Arduino can be seen on the left side of the picture, obscured by one of the column supports. It needs to be connected to a computer running the control application for the device to work. At the bottom, the device is supported by adjustable, metal legs that are typically used for furniture.



Figure 6-1. The Complete Physical Device

The led array can be seen in Figure 6-2 shining downwards from the bottom of the device. Here the LEDs are outputting 100% of rated current, with scaling current limits also programmed for the 572nm and 950nm drivers. This was done to prevent high temperatures, as their respective driver boards were heating beyond 100°C at their nominal rated current values. Additionally, the 950nm current also needed to be derated due to the LED array exceeding 40°C. The rest of the drivers had acceptable temperatures at full load, unlikely to surpass 70°C at normal room temperature.



Figure 6-2. LED Array Shining Downwards from Device

6.2 Non-Uniformity

For non-uniformity testing, the ASTM procedure of dividing the test area (6in x 6in) into 36 squares was used. Irradiance measurements were then taken at the center of each square with an irradiance meter approximately 4 cm. from the LED array. The resulting irradiance map can be seen in Figure 6-3.

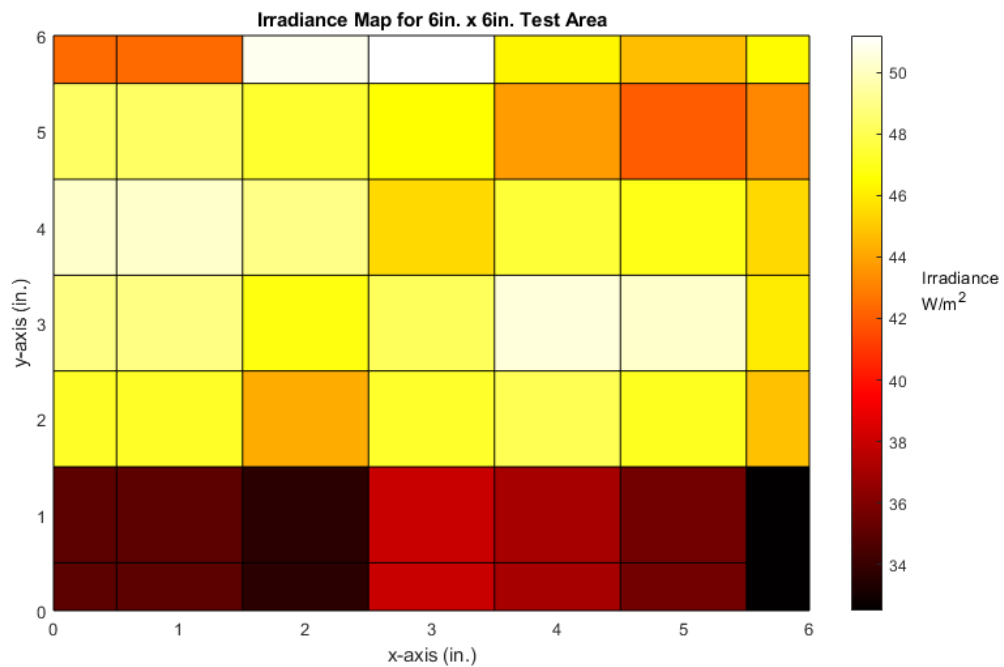


Figure 6-3. Measured Irradiance Map

The non-uniformity can be calculated using the equation below [16].

$$Non - uniformity(\%) = \frac{\max irradiance - \min irradiance}{\max irradiance + \min irradiance} * 100\% \quad \text{Equation 6-1}$$

From the irradiance values measured, the non-uniformity for the specified test area comes out to be 22.34%, which is out of the ASTM standard. This is mainly due to the low irradiance area at the bottom of the map. If we were to constrict the test area to a 5in. x 6in. area excluding this low irradiance strip, the device's non-uniformity would then be 9.87%, which would barely meet the ASTM class C standard for non-uniformity.

6.3 Spectral Output

Shown below in Figure 6-4 is the measured spectral output of the solar simulator using the recommended scaling values from MATLAB. Immediately, we can notice an anomalous amount of spectral content in the 900 – 1100nm region that is not due to the 950nm LEDs.

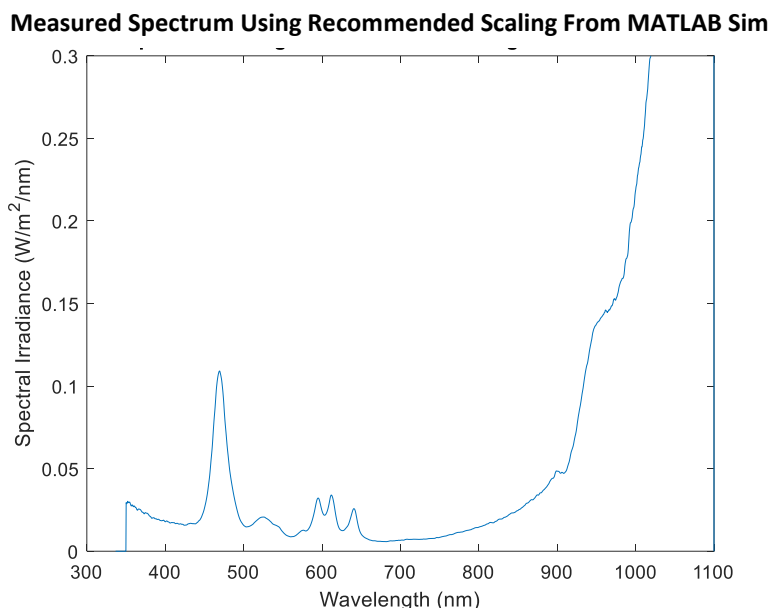


Figure 6-4. Measured Spectrum at Recommended Scaling Values

Spectral measurements were also taken at maximum output to compare with values from the MATLAB simulation. These are shown in Figures 6-5 and 6-6. It can be seen that the spectral irradiance peak of the 470nm LEDs is very overpowering compared to the others. And in general, all peaks appear larger than the simulation values.

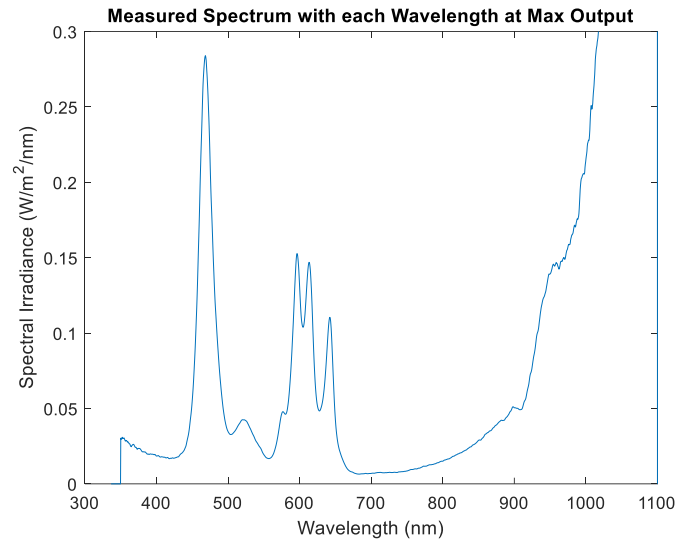


Figure 6-5. Measured Spectrum with all LEDs at Max Output

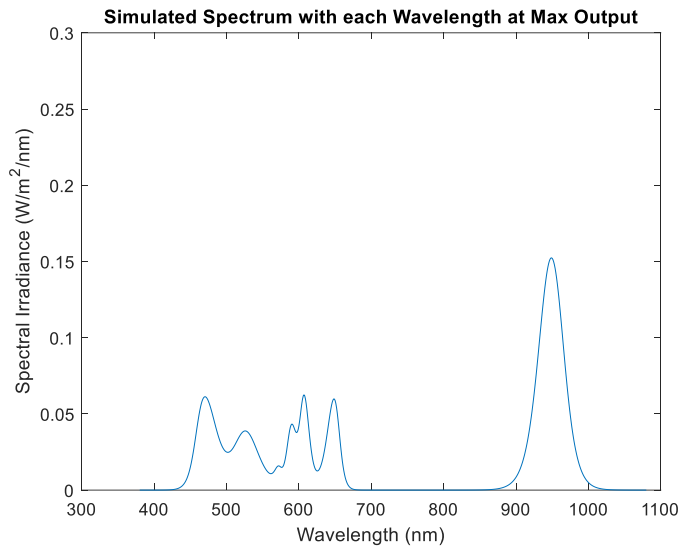


Figure 6-6. Simulated Spectrum with all LEDs at Max Output

6.4 Temporal Instability

Two temporal stability tests were run for ten minutes. The first test used recommended tuning values that were determined in MATLAB for best matching with ASTM spectral match requirements. The second test had all drivers set to 50% of their max output.

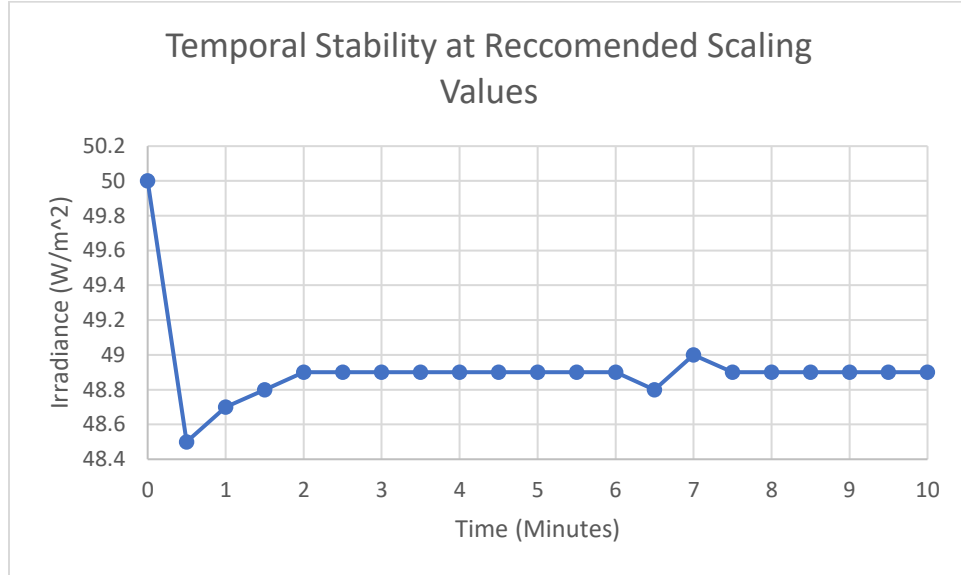


Figure 6-7. Temporal Stability Measurements at Recommended Scaling Values

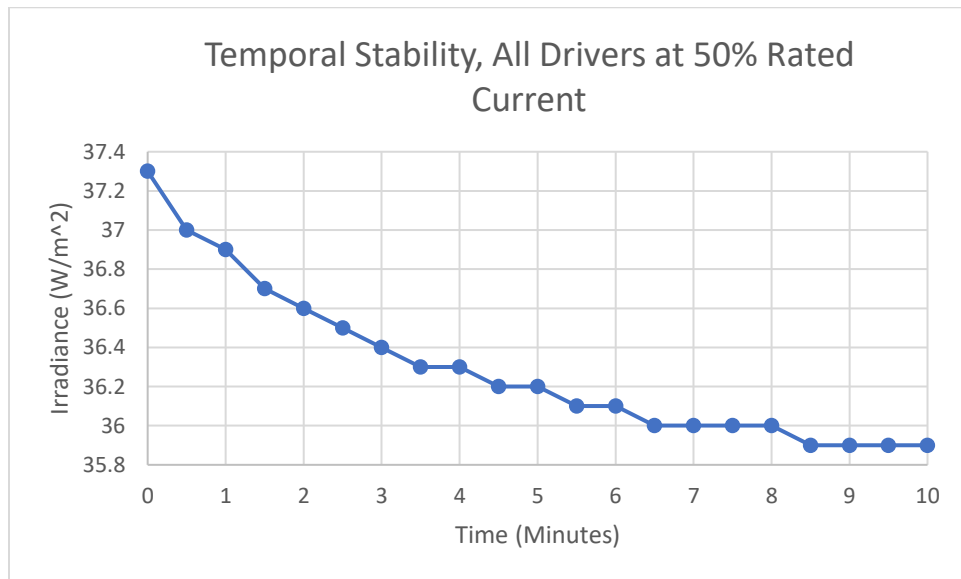


Figure 6-8. Temporal Stability Measurements at 50% Max Output for All Drivers

To calculate temporal instability, Equation 6-1 is used again. In this case, the min and max values correspond to the minimum and maximum irradiances measured in the time frame. For the first test, the temporal stability was 1.52%. For the second test, the temporal stability was 1.91%. Both these values put us within the ASTM Class A for temporal stability. It is assumed that good temporal stability would be harder to achieve for a device with a higher irradiance output.

Chapter 7. Conclusion

7.1 Summary of Results

Overall, we built a tunable LED-Based Solar simulator that covered most of the visible light region and some of the IR region using LEDs provided by ROHM Semiconductor and boost LED Drivers provided by Analog Devices. The device was able to output up to around 0.05 suns in the specified test area of 6in. x 6in. Ideally, we would have wanted something that could have output up to 1 sun, or $1000\text{W}/\text{m}^2$ within the test area, but that was not feasible with the provided LEDs. It was also tunable via a PC-based application used to scale the irradiance output of individual wavelengths. In regards to non-uniformity, we were not able to get within ASTM class C requirements. To do so, we would need to reduce the area to exclude the strip of area which had low irradiance measurements. As for spectral content, we were able to cover the visible light region and IR region around 950nm, but had a large gap was present between the two areas. This made spectral match evaluations difficult, as the standard assumes coverage from 400nm to 1100nm. Our goal was then to aim for a good spectral match in the visible light region (400nm - 700nm), but this involved scaling the output of the 950nm LEDs a lot higher than the rest of the LEDs to compensate for the empty spectral region. And for temporal stability, we were within ASTM class A requirements for a period of 10 minutes.

The device was powered by 120VAC as required, with all power electronics and higher voltage wires kept inside a plastic enclosure. Also, current derating was only an issue with the 950nm LED, as the temperature of the array board can reach around 45°C at max output which necessitates limiting the 950nm LEDs' currents $<60\text{mA}$. This current derating was implemented programmatically. Also, the 572nm driver board was reaching temperatures near 100°C at max output, so a current limit was programmed for it as well.

7.2 Future Improvements

This project could be improved by the inclusion of LEDs within the range of 600-900nm and $>1000\text{nm}$, and maybe even UV LEDs. This would greatly improve the tunability range of the device and allow for better spectral matching. To achieve a higher irradiance output, higher power LEDs could also be used. However, this also introduces the need to implement an adequate cooling system to account for greater heat dissipation.

One problem that went unsolved was the issue with the boost converters that were used. In the end, the converters were not able to operate in boost mode and instead had to operate under the condition where V_{IN} exceeded V_{OUT} . This necessitated the use of two different DC power supplies, as having a single power supply would cause excessive power

dissipation across several of the driver boards. Future designs could try implementing an improved PCB layout or a different LED driving scheme.

As for our simulation method, the simulated coverage appears to match our experimental coverage, but the spectral irradiance peaks tend to be much higher experimentally. Still, the simulation can be modified with more scaling so that it matches the measured spectral output. However, due to lack of time and access to lab space, this could not be done in time.

7.3 Reflection

Overall, this was a great project to work on and a very educational experience for me. This project allowed me to develop my skills in PCB design and gain more confidence in soldering both through-hole and SMD components. It also gave me the opportunity to learn more about LEDs and LED drivers. This includes LED simulation, photometry, and radiometry. There was a lot that I did not know going into this project, but with the aid of Dr. Dolan along with my own research, I was able to learn a lot.

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Appendices

Appendix A. ABET Senior Project Analysis

Project Title: LED-Based Solar Simulator

Student's Name: Jonathan Honrada Student's Signature: JonH

Advisor's Name: Dale Dolan Advisor's Initials: Date:

1. Summary of Functional Requirements

This LED-based solar simulator replicates sunlight in an indoor laboratory setting for conducting tests with individual solar cells. It exceeds the ASTM C solar simulator standards for spectral match, uniformity, and stability of output. The spectral output of the device is also tunable at specified wavelengths and in overall intensity, allowing users to conduct tests with custom spectrums of light.

2. Primary Constraints

One difficulty in this project is that the radiometric characteristics of these LEDs to be used are not given. This data is missing from the ROHM datasheets I have looked at so far (although they do provide photometric data) [8]. This information is necessary for the design phase of this project as it will be used for simulations and determining how many LEDs and LED drivers will need to be used for a designed implementation. It also defines power requirements for the PCB.

Another difficulty is the impact that COVID-19 will potentially have on the project. Access to laboratory space has to be planned a few weeks ahead of time, so any delays or shortcomings may lead to missing a testing opportunity at Cal Poly. This project will also eventually involve having a custom PCB manufactured and shipped to my location. Research into possible manufacturers, showed many from China, with a realistic shipping time frame of around 15 business days or three weeks. The impact of COVID-19 may extend this time frame even more. The constraint here will be finding a manufacturer that is able to fabricate and ship my PCB as quickly as possible, is affordable (< \$100), and is known to be reliable.

3. Economic

This device would aid in testing and research of solar cells and panels, contributing somewhat towards achieving a greener future where renewable sources of energy are more widespread, and people are better-informed about energy concerns.

Regarding monetary matters, as the manager and designer of this project, I will provide the capital needed for this project plus the \$200 allotted by Cal Poly's Electrical Engineering

Department. Using my original cost estimations as a basis, I would expect this project to cost around \$300 to \$400. Therefore, the \$200 from Cal Poly will be used completely and I will provide \$100 to \$200 of my own capital for this project.

This project also has a heavy dependency on manufactured parts. This project requires LEDs and LED Drivers manufactured by ROHM as well as various electrical components produced by other manufacturers. The PCB in this project will also need to be produced by an outside manufacturer. Material for the device structure will also need to be manufactured.

Being that this project requires many manufactured components, one obvious impact is the environmental cost of manufacturing and shipping all those components. ROHM Semiconductor does however have a well-defined environmental policy, which indicates they will be a good manufacturer to source parts from [17]. I cannot comment on other manufacturers as they have not yet been decided. Aside from manufacturing, testing the device during the design phase as well as operating the final device requires electric power, of which most is still generated by fossil fuels [18].

Costs accrue in the design phase of this project. These costs include the theoretical cost of labor, manufacturing and shipping of components, time spent operating test equipment, time spent with the advisor, and travel between my house and Cal Poly (about a 30 mile drive). The estimated development time of this project is 224 hours as previously determined in Table 4-2. Assuming a proper manufacturing structure is developed, the build time for a single device should be around 6.5 hours. After the device is completed, maintenance would be minimal because LEDs will last long. Further upgrades or different solutions could be ideas for a future senior project.

4. If manufactured on a commercial basis:

It is anticipated that if commercialized, this device's main customers would be other universities. There are 4,298 universities in the United States, so assuming ~10% of these universities are interested and decide to purchase a trial device, that would equate to 430 devices sold.

Table A-1. Manufacturing Cost Estimation

Component	Price
1 PCB	\$20.00
LEDs and LED Drivers	\$97.00
Other Electrical Components	\$30.00
Structural Material	\$80.00
Labor To Build and Test (6 hours at \$18.50/hour)	\$111.00
Total Cost	\$338.00

With the purchase price of the device placed at \$500.00, the total profit is calculated below.

$$Profit = N \times (\$500.00 - \$338.00) \text{ where } N = 430$$

$$Profit = \$69,660$$

The total user cost would be the purchase price of \$500 plus the power to operate the device, which would depend on the final device's power consumption and the cost of electricity for the user.

5. Environmental

There are various environmental impacts throughout this project. PCB manufacturing would use copper as well as a variety of chemicals. The structure of the project may use some kind of plastic. Shipping of parts for this project also involves all the environmental impacts of driving, including collisions with animals and the use of gasoline. The project also uses electric power from the grid, of which the majority is sourced from fossil fuels [18].

6. Manufacturability

If this device were to be manufactured, issues would arise in how the process could be streamlined and made less expensive. This would involve establishing a division of labor based on various stages of building the device. These stages would include PCB construction, board-testing, final device construction, and quality control before shipping. It would be worthwhile to invest in a PCB machine that would be manned by an operator. We would also need to define standards that must be met before progressing to the next stage in the manufacturing process.

7. Sustainability

ROHM LEDs can last long, provided their forward current decreased in hot temperatures. It would be advised not to operate the device in a room with bad airflow or in an environment with high ambient temperatures. Similar projects implemented cooling when needed, so it may be necessary to install heatsinks and fans if discovered that the device gets too hot during testing.

By enabling the testing of solar devices, this device will positively impact the future sustainable use of renewable resources.

One potential upgrade creating a feedback loop by integrating the tested solar loop into the system. The device would then run a self-calibration to maximize the power output of the solar simulator. Other potential upgrades could explore different LED arrangements, including the implementation of special optics or hybrid combinations with non-LED lamps.

Upgrading the device may require a complete redesign of the implemented PCB as well as a change in device power requirements. However, the structure of the device could still be reused if the spatial requirements remain the same.

8. Ethical

The primary ethical motivation for this device is in its contribution towards creating a greener future with less reliance on non-renewable sources of energy. Continued usage of non-renewable energy is not sustainable, and the emissions produced by doing so continue to harm the environment. From a consequentialist perspective, it is easy to see the ethical concern here. The consequences of not pursuing research into better forms of energy could lead to the downfall of civilization, as we are slated to run out of natural gas and oil this century. Even from a duty-based ethical system, it would not be difficult to formulate a duty based on the pursuit and encouragement of renewable energy systems. This could relate to the idea of intergenerational ethics, which establishes a duty towards future generations.

With respect to the IEEE code of ethics, code number one applies very strongly to this project [19]. Code 1 states that one should “strive to comply with ethical design” and “disclose promptly factors that might endanger the public or environment.” As stated in section 9 of this analysis, the device will be built with a strong concern for the safety of the user, and any potential hazards that are discovered in the design process will be corrected or disclosed. Code 5 also applies to this project. It states that I should “seek, accept ... criticism of technical work,” which is important since there are many aspects of this project that I am not an expert on.

9. Health and Safety

One health concern associated with the manufacture of this device is the use of lead-based solder. Exposure to lead can lead to reproductive problems and muscle pain. Exposure to solder fumes can also lead to respiratory problems.

Safety concerns also arise when it comes to device operation. Since this device is powered by 120VAC, power electronics must be enclosed, and the enclosure must be grounded if it is made of metal. The bright LED light output of the device could also be blinding if stared at directly, so a labeled warning and shield must be on the device to keep users safe and aware.

10. Social and Political

This project is related to sources of energy, which could be considered a political issue. However, there is a strong consensus among many adults regardless of political affiliation in support of solar energy. Therefore, it is doubtful that this device will have a strong political impact in of itself, nor will its development be limited by political concerns.

The project will impact the users by giving them the opportunity to conduct solar testing. This indirectly has a positive effect on people in the future, as solar-related research will lead to a greener future.

To account for users in other countries, the project would need to be designed in a way that accounts for different power systems. The system will also be designed to work in tandem with a computer, but computer requirements will be very low so that more users are able to use the device. To accommodate users with vision problems, computer text will be appropriately sized. Colorblind individuals may have difficulty discerning colors between different wavelengths of light, but wavelengths will be labeled by their numerical value along with a sample of their color.

11. Development

This project will require me to learn a lot of new things as well as develop my current skills. Part of this project will require me to improve my soldering skills (both thru-hole and SMD components) and my ability to efficiently create a PCB layout. In order to simulate the solar simulator before constructing it, I will need to create a simulation model in a tool such as MATLAB. This will require me to learn more about and understand the photometric and radiometric characteristics of LEDs.

Appendix B. MATLAB Simulation Code

```
% Solar Simualtor Light and Irradiance Simulation
% Jonathan Honrada EE461 462 'LED Based Solar Simulator'
close all;
format short;
format compact;
hold off;

%% wavelength x-axis
lambda = 380:1:1080;

%% create spectral distribution models f(lambda) for each LED based on datasheet
%
% Using model defined in [3]Solar spectrum matching using monochromatic leds
% Parameters [A, wlc1, wlc2, w1, w2]
Param_630 = [1.91,644,654,7,4];
Exp1 = exp(-(lambda-Param_630(2))./Param_630(4))+1;
Exp2 = exp((lambda-Param_630(3))./Param_630(5))+1;
Fsim_630 = (Param_630(1))./(Exp1.*Exp2);

Param_620 = [2.9,627,631,6,5.5];
Exp1 = exp(-(lambda-Param_620(2))./Param_620(4))+1;
Exp2 = exp((lambda-Param_620(3))./Param_620(5))+1;
Fsim_620 = (Param_620(1))./(Exp1.*Exp2);

Param_605 = [2.15,604,610,3.5,4.8];
Exp1 = exp(-(lambda-Param_605(2))./Param_605(4))+1;
Exp2 = exp((lambda-Param_605(3))./Param_605(5))+1;
Fsim_605 = (Param_605(1))./(Exp1.*Exp2);

Param_590 = [3.2,588,590,4,5];
Exp1 = exp(-(lambda-Param_590(2))./Param_590(4))+1;
Exp2 = exp((lambda-Param_590(3))./Param_590(5))+1;
Fsim_590 = (Param_590(1))./(Exp1.*Exp2);

Param_572 = [3.02,571,573,4,3];
Exp1 = exp(-(lambda-Param_572(2))./Param_572(4))+1;
Exp2 = exp((lambda-Param_572(3))./Param_572(5))+1;
Fsim_572 = (Param_572(1))./(Exp1.*Exp2);

Param_565 = [3.05,564,566,3,4];
Exp1 = exp(-(lambda-Param_565(2))./Param_565(4))+1;
Exp2 = exp((lambda-Param_565(3))./Param_565(5))+1;
Fsim_565 = (Param_565(1))./(Exp1.*Exp2);

Param_528 = [2.7,520,530,10,13];
Exp1 = exp(-(lambda-Param_528(2))./Param_528(4))+1;
Exp2 = exp((lambda-Param_528(3))./Param_528(5))+1;
Fsim_528 = (Param_528(1))./(Exp1.*Exp2);

Param_470 = [1.68,460,480,6,11];
Exp1 = exp(-(lambda-Param_470(2))./Param_470(4))+1;
Exp2 = exp((lambda-Param_470(3))./Param_470(5))+1;
Fsim_470 = (Param_470(1))./(Exp1.*Exp2);

Param_875 = [2,865,890,14,13];
Exp1 = exp(-(lambda-Param_875(2))./Param_875(4))+1;
```

```

Exp2 = exp((lambda-Param_875(3))./Param_875(5))+1;
Fsim_875 = (Param_875(1))./(Exp1.*Exp2);

Param_950 = [1.8,938,960,11,10];
Exp1 = exp(-(lambda-Param_950(2))./Param_950(4))+1;
Exp2 = exp((lambda-Param_950(3))./Param_950(5))+1;
Fsim_950 = (Param_950(1))./(Exp1.*Exp2);
figure
plot(lambda,Fsim_950)
xlim([900, 1000])
xticks([900:10:1000])
ylim([0, 1])
yticks([0:0.1:1])

%% calculation method defined by Simulation Source (remember to add)
% datasheet Iv (luminous intensity) values [candelas] for selected LEDs
% (remember: add sources to references)
Iv_630 = 0.280;      %SML-Z14V4T RED          2.0 VF; 50mA, 280mcd
%Iv_620 = 0.560;      %SML-Z14U4T RED          2.0 VF; 50mA, 560mcd
Iv_605 = 0.710;      %SML-Z14D4T ORANGE        2.0 VF; 50mA, 710mcd
Iv_590 = 0.710;      %SML-Z14Y4T YELLOW        2.1 VF; 50mA, 710mcd
Iv_572 = 0.224;      %SML-Z14M4T YELLOW-GREEN  2.1 VF; 50mA, 224mcd
%Iv_565 = 0.120;      %SML-Z14F4T GREEN        2.1 VF; 50mA, 120mcd
%E_561 = 0.056;      %SML-Z14P4T GREEN        2.1 VF; 50mA, 56 mcd
Iv_528 = 1.100;      %SMLZ14EGT(A) GREEN      3.4 VF; 20mA, 1100mcd
Iv_470 = 0.300;      %SMLZN4BGT(A) BLUE       3.3 VF; 20mA, 300mcd

Ie_875 = 0.040;
Ie_950 = 0.014;

%% calculate luminous intensity to radiant intensity conversion factor
% using datasheet spectral distribution and luminosity function v(lambda)
lumeff_t = readmatrix('lum_eff2.csv');
Conv_630 = (sum(Fsim_630))/(683*sum(Fsim_630.*lumeff_t));
Conv_620 = (sum(Fsim_620))/(683*sum(Fsim_620.*lumeff_t));
Conv_605 = (sum(Fsim_605))/(683*sum(Fsim_605.*lumeff_t));
Conv_590 = (sum(Fsim_590))/(683*sum(Fsim_590.*lumeff_t));
Conv_572 = (sum(Fsim_572))/(683*sum(Fsim_572.*lumeff_t));
Conv_565 = (sum(Fsim_565))/(683*sum(Fsim_565.*lumeff_t));
Conv_528 = (sum(Fsim_528))/(683*sum(Fsim_528.*lumeff_t));
Conv_470 = (sum(Fsim_470))/(683*sum(Fsim_470.*lumeff_t));

%% define set height in [cm]
h = 8.1;

%% assign x y coordinates in [cm] by wavelength
% using imported data organized in excel
Pos_630 = readmatrix('Pos_630.csv');
Pos_605 = readmatrix('Pos_605.csv');
Pos_590 = readmatrix('Pos_590.csv');
Pos_572 = readmatrix('Pos_572.csv');
Pos_528 = readmatrix('Pos_528.csv');
Pos_470 = readmatrix('Pos_470.csv');
%Pos_875 = readmatrix('Pos_875.csv');
Pos_950 = readmatrix('Pos_950.csv');
[X,Y] = meshgrid(0:0.1:22);

```

```

%% irradiance map calcs
% for each LED wavelength, compute illuminance map on test plane then convert to
irradiance
% calculate spectral irradiance function S(lambda) using formula shown in [3]
% cosine correction factor used, apex angle ~120 deg for all visible light leds
(470 to 630nm), near Lambertian source
% cosine factor scaled for IR led (875nm) for apex angle of 18 deg
Z_630 = zeros(221);
for n = 1:size(Pos_630,1)
cos_factor = cos(atan(sqrt((abs(X-Pos_630(n,1))).^2+(abs(Y-
Pos_630(n,2))).^2)./h)./2);
Z_630 = Z_630 + (Iv_630./((0.01*sqrt((abs(X-Pos_630(n,1))).^2+(abs(Y-
Pos_630(n,2))).^2+h.^2).^2)).*cos_factor;
end
Emap_630 = Conv_630.*Z_630;
Emap_630_mean = mean(Emap_630,'all');
S_630 = Emap_630_mean.*Fsim_630./trapz(Fsim_630);

Z_605 = zeros(221);
for n = 1:size(Pos_605,1)
cos_factor = cos(atan(sqrt((abs(X-Pos_605(n,1))).^2+(abs(Y-
Pos_605(n,2))).^2)./h)./2);
Z_605 = Z_605 + (Iv_605./((0.01*sqrt((abs(X-Pos_605(n,1))).^2+(abs(Y-
Pos_605(n,2))).^2+h.^2).^2)).*cos_factor;
end
Emap_605 = Conv_605.*Z_605;
Emap_605_mean = mean(Emap_605,'all');
S_605 = Emap_605_mean.*Fsim_605./trapz(Fsim_605);

Z_590 = zeros(221);
for n = 1:size(Pos_590,1)
cos_factor = cos(atan(sqrt((abs(X-Pos_590(n,1))).^2+(abs(Y-
Pos_590(n,2))).^2)./h)./2);
Z_590 = Z_590 + (Iv_590./((0.01*sqrt((abs(X-Pos_590(n,1))).^2+(abs(Y-
Pos_590(n,2))).^2+h.^2).^2)).*cos_factor;
end
Emap_590 = Conv_590.*Z_590;
Emap_590_mean = mean(Emap_590,'all');
S_590 = Emap_590_mean.*Fsim_590./trapz(Fsim_590);

Z_572 = zeros(221);
for n = 1:size(Pos_572,1)
cos_factor = cos(atan(sqrt((abs(X-Pos_572(n,1))).^2+(abs(Y-
Pos_572(n,2))).^2)./h)./2);
Z_572 = Z_572 + (Iv_572./((0.01*sqrt((abs(X-Pos_572(n,1))).^2+(abs(Y-
Pos_572(n,2))).^2+h.^2).^2)).*cos_factor;
end
Emap_572 = Conv_572.*Z_572;
Emap_572_mean = mean(Emap_572,'all');
S_572 = Emap_572_mean.*Fsim_572./trapz(Fsim_572);

Z_528 = zeros(221);
for n = 1:size(Pos_528,1)
cos_factor = cos(atan(sqrt((abs(X-Pos_528(n,1))).^2+(abs(Y-
Pos_528(n,2))).^2)./h)./2);
Z_528 = Z_528 + (Iv_528./((0.01*sqrt((abs(X-Pos_528(n,1))).^2+(abs(Y-
Pos_528(n,2))).^2+h.^2).^2)).*cos_factor;
end
Emap_528 = Conv_528.*Z_528;

```

```

Emap_528_mean = mean(Emap_528, 'all');
S_528 = Emap_528_mean.*Fsim_528./trapz(Fsim_528);

Z_470 = zeros(221);
for n = 1:size(Pos_470,1)
    cos_factor = cos(atan(sqrt((abs(X-Pos_470(n,1))).^2+(abs(Y-
    Pos_470(n,2))).^2)./h)./2);
    Z_470 = Z_470 + (Iv_470./((0.01*sqrt((abs(X-Pos_470(n,1))).^2+(abs(Y-
    Pos_470(n,2))).^2+h.^2).^2)).*cos_factor;
end
Emap_470 = Conv_470*Z_470;
Emap_470_mean = mean(Emap_470, 'all');
S_470 = Emap_470_mean.*Fsim_470./trapz(Fsim_470);

Z_950 = zeros(221);
for n = 1:size(Pos_950,1)
    m = -log10(2)/log10(cosd(15)); %scaling factor for non-Lambertian source
    cos_factor = cos(atan(sqrt((abs(X-Pos_950(n,1))).^2+(abs(Y-
    Pos_950(n,2))).^2)./h)./2);
    Z_950 = Z_950 + (Ie_950./((0.01*sqrt((abs(X-Pos_950(n,1))).^2+(abs(Y-
    Pos_950(n,2))).^2+h.^2).^2)).*(cos_factor.^m);
end
Emap_950 = Z_950;
Emap_950_mean = mean(Z_950, 'all');
S_950 = Emap_950_mean.*Fsim_950./trapz(Fsim_950);

%% Current Limiting Factor
lim_572 = 0.9;
lim_950 = 0.6;

%% Scale factors for each wavelength
% adjusted manually attempting to match ASTM standards for spectral match
A_630 = 0.2;
A_605 = 0.20;
A_590 = 0.20;
A_572 = 0.1*lim_572;
A_528 = 0.3;
A_470 = 0.33;
%A_875 = 0.45;
A_950 = 1*lim_950;

%% Calculate total spectral distribution
S_total = A_630*S_630 + A_605*S_605 + A_590*S_590 + A_572*S_572 + A_528*S_528 +
A_470*S_470 + A_950*S_950;

%% Calculate total irradiance map
Emap_total = A_630*Emap_630...
+ A_605*Emap_605...
+ A_590*Emap_590...
+ A_572*Emap_572...
+ A_528*Emap_528...
+ A_470*Emap_470...
+ A_950*Emap_950;

%% Create irradiance map of test area (6" x 6")
E_testarea = Emap_total(35:185,35:185);

%% Calculate area %'s based on ASTM specified regions
Total_area = trapz(S_total)

```

```

Area_400_500 = trapz(S_total(21:120))/Total_area*100
Area_500_600 = trapz(S_total(121:220))/Total_area*100
Area_600_700 = trapz(S_total(221:320))/Total_area*100
Area_700_800 = trapz(S_total(321:420))/Total_area*100
Area_800_900 = trapz(S_total(421:520))/Total_area*100
Area_900_1100 = trapz(S_total(521:701))/Total_area*100
astm15g = 0.1*readmatrix('astm_15g.csv');

%% Plot total spectrum and total irradiance map
[X_test,Y_test] = meshgrid(0:0.1:15);

figure(1)
hold on;
plot(lambda, S_total)
plot(lambda, astm15g)
xlabel('Wavelength (nm)')
ylabel('Spectral Irradiance (W/m^2/nm)')
hold off;
figure(2)
surf(X_test,Y_test,E_testarea);
xlabel('x-axis (cm)')
ylabel('y-axis (cm)')
zlabel('Irradiance (W/m^2)')
colormap(hot);

```

Appendix C. LT3760 Driver Schematic

